

REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE 1 October 1998		3. REPORT TYPE AND DATES COVERED
4. TITLE AND SUBTITLE EFFECTS OF GENU RECURVATUM ON POSTURAL CONTROL: A PRELIMINARY STUDY			5. FUNDING NUMBERS	
6. AUTHOR(S) THOMAS SWINSON				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) The University of North Carolina at Chapel Hill			8. PERFORMING ORGANIZATION REPORT NUMBER  98-080	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) THE DEPARTMENT OF THE AIR FORCE AFIT/CIA, BLDG 125 2950 P STREET WPAFB OH 45433			10. SPONSORING/MONITORING AGENCY REPORT NUMBER	
11. SUPPLEMENTARY NOTES				
12a. DISTRIBUTION AVAILABILITY STATEMENT Unlimited Distribution In Accordance With 35-205/AFIT Sup 1			12b. DISTRIBUTION CODE	
13. ABSTRACT (Maximum 200 words)				
14. SUBJECT TERMS			15. NUMBER OF PAGES 65	
			16. PRICE CODE	
17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT	

19981009 066

**EFFECTS OF GENU RECURVATUM  
ON POSTURAL CONTROL:  
A PRELIMINARY STUDY**

By

J. Thomas Swinson, PT  
Major, USAF, BSC

A thesis submitted to the faculty of the University of North Carolina at Chapel Hill in  
partial fulfillment of the requirements for the degree of Master of Science in the  
Department of Allied Health Professions, Division of Physical Therapy

Chapel Hill

1998

Approved by:

**DISTRIBUTION STATEMENT A**

Approved for public release;  
Distribution Unlimited

Michael T. Gross Advisor  
Michael T. Gross, PT, Ph.D.

Bing Yu Reader  
Bing Yu, Ph.D.

Philip L. Witt Reader  
Philip L. Witt, PT, Ph.D.

## **ABSTRACT**

**J. Thomas Swinson: Effects of Genu Recurvatum on  
Postural Control: A Preliminary Study  
(under the direction of Michael T. Gross, PT, Ph.D.)**

Genu recurvatum has been associated with proprioception deficits and a predisposition to knee ligament injury. The primary purpose of this study was to investigate the effects of genu recurvatum on two common tests of postural control. Eleven subjects with bilateral genu recurvatum were matched with 11 controls. Force plate data were acquired while subjects were tested for steadiness during one leg standing balance and the balance leg reach test. Results failed to demonstrate a significant difference between groups except for the measure of maximum anterior-posterior sway during the functional balance leg reach test. All force plate variables indicated significant postural unsteadiness in the balance leg reach test compared to the one leg stance test. Clinicians might consider combining force plate data with functional testing to enhance the predictive value of these tests.

## SELECTED REFERENCES

1. Arangio GA, St. Amour-Meyers M, Reed J: Incidence of asymptomatic nontraumatic unilateral knee hyperextension in the high school athlete. *J Sports Rehab* 5:287-292, 1966
2. Axe MJ, Lindsay K, Snyder-Mackler L: The relationship between knee hyperextension and articular pathology in the ACL deficient knee. *J Sports Rehab* 5:120-126, 1996
3. Barrack RL, Skinner HB, Cook SD: Proprioception of the knee joint. (Paradoxical effect of training). *Am J Phys Med* 63(4):174-181, 1984
4. Beighton P, Solomon L, Soskolne CL: Articular mobility in an African population. *Ann Rheum Dis* 32:413-418, 1973
5. Berg KO, Maki BE, Williams JJ, Holliday PJ, Wood-Dauphinee SL: Clinical and laboratory measures of postural balance in an elderly population. *Arch Phys Med Rehab* 73:1073-1080, 1992
6. Bohannon RW, Larkin PA, Cook AC, Gear J, Singer J: Decrease in timed balance test scores with aging. *Phys Ther* 64(7):1067-1070, 1984
7. Bolgia LA, Keskula DR: Reliability of lower extremity functional performance tests. *JOSPT* 26:138-149, 1997
8. Cohen J: Statistical power analysis for the behavioral sciences, (2<sup>nd</sup> ED), pp 273-311, Hillsdale, NJ: Lawrence Erlbaum Associates, Pub, 1988
9. DeHaven KE, Lintner DM: Athletic injuries: Comparison by age, sport, and gender. *Am. J Sports Med* 14(3):218-224, 1986
10. Ekdahl C, Jarnlo G, Andersson SI: Standing balance in healthy subjects: evaluation of a quantitative test battery on a force platform. *Scand J Rehab Med* 21:187-195, 1989
11. Era P, Heikkinen E: Postural sway during standing and unexpected disturbance of balance in random samples of men of different ages. *J Gerontol* 40(3):287-296, 1985
12. Friden T, Zatterstrom R, Lindstrand A, Moritz U: A stabilometric technique for evaluation of lower limb instabilities. *Am J Sports Med* 17(1):118-122, 1989
13. Friden T, Zatterstrom R, Lindstrand A, Moritz U: Disability in anterior cruciate ligament insufficiency, an analysis of 19 patients. *Acta Orthop Scand* 61(2):131-135, 1990

14. Geurts AC, Nienhuis B, Mulder T: Intrasybect variability of selected force-platform parameters in the quantification of postural control. *Arch Phys Med Rehab* 74:1144-1150, 1993
15. Greenberger HB, Sperling L, Frankford G: The rationale and reliability of three functional performance tests in the assessment of lower extremity function. Platform Presentation, CSM, APTA. *JOSPT* 23(1):64, 1996
16. Hall M, Ferrell W, Sturrock R, Hamblen D, Baxendale R: The effect of the hypermobile syndrome on knee joint proprioception. *Br J Rheum* 34:121-125, 1995
17. Harrison E, Duenkel N, Dunlop R, Russell G: Evaluation of single leg standing following ACL surgery and rehabilitation. *Phys Ther* 74(3):245-253, 1994
18. Horak FB: Clinical Measurement of postural control in adults. *Phys Ther* 67(12):1881-1885, 1987
19. Huston LJ, Wojtys EM: Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med* 24(4):427-436, 1996
20. Kalenak A, Morehouse CA: Knee stability and knee ligament injuries. *JAMA* 234(11):11443-1145, 1975
21. Lepart SM, Pincivero DM, Giraldo JL, Fu FH: The role of proprioception in the management and rehabilitation of athletic injuries. *Am J Sports Med* 25(1):130-137, 1997
22. Loudon J, Jenkins W, Loudon K: The relationship between static posture and ACL injury in female athletes. *JOSPT* 24(2):91-97, 1996
23. Mizuta H, Sharaishi M, Kubota K, Kai K, Takagi K: A stabilometric technique for evaluation of functional instability in anterior cruciate ligament-deficient knee. *Clin J Sports Med* 2:235-239, 1992
24. Moretz JA, Walters R, Smith L: Flexibility as a predictor of knee injuries in college football players. *Phys Sports Med* 10(7):93-97, 1982
25. Murray MP, Seireg AA, Sepic SB: Normal postural stability and steadiness: quantitative assessment. *J Bone Joint Surg* 57A(4):510-515, 1975
26. Nicholas JA: Injuries to knee ligaments, relationship to looseness and tightness in football players. *JAMA* 212(13):2236-2239, 1970

27. Noyes F, Barber S, Mangine R: Abnormal lower limb symmetry determined by function hop tests after ACL rupture. *Am. J Sports Med* 19(5):513-518, 1991
28. Prieto TE, Myklebust JB, Hoffman RG, Levetl EG, Myklebust BM: Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Trans Biomed Eng* 43(9):956-966, 1996
29. Qualter R, Kowalsky D, Helgren M: The reliability and validity of a unilateral balance and contralateral reach test for ACL insufficiency. Platform Presentation, CSM, APTA. *JOSPT* 23(1):91, 1996
30. Schenkman M: Interrelationship of neurological and mechanical factors in balance control. In: Duncan PW, ed. *Balance, Proceedings of the APTA Forum*, 29-41, 1990
31. Snyder-Mackler L, Fitzgerald G, Barolozzi A, Ciccotti M: Relationship between passive joint laxity and functional outcome after ACL injury. *Am. J Sports Med* 25(2):191-195, 1997
32. Tropp H, Ekstrand J, Gillquist J: Stabilometry in functional instability of the ankle and its value in predicting injury. *Med Sci Sports Ex* 16(1):64-66, 1984
33. Tropp H, Odenkirk P: Postural control in single limb stance. *J Orth Res* 6(6):833-839, 1988
34. Woodford-Rogers B, Cyphert L, Denegar CR: Risk factors for ACL injury in high school and college athletes. *J Athl Train* 29(4):343-346, 1994
35. Zatterstrom R, Frieden T, Lindstrand A, Moritz U: The effect of physiotherapy on standing balance in chronic ACL insufficiency. *Am J Sports Med* 22(4):531-536, 1994

**EFFECTS OF GENU RECURVATUM  
ON POSTURAL CONTROL:  
A PRELIMINARY STUDY**

By


J. Thomas Swinson, PT  
Major, USAF, BSC

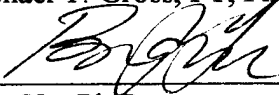
A thesis submitted to the faculty of the University of North Carolina at Chapel Hill in  
partial fulfillment of the requirements for the degree of Master of Science in the  
Department of Allied Health Professions, Division of Physical Therapy

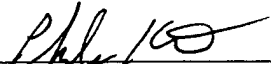
Chapel Hill

1998

Approved by:

 Advisor  
Michael T. Gross, PT, Ph.D.

 Reader  
Bing Yu, Ph.D.

 Reader  
Philip L. Witt, PT, Ph.D.

## **ABSTRACT**

**J. Thomas Swinson: Effects of Genu Recurvatum on  
Postural Control: A Preliminary Study  
(under the direction of Michael T. Gross, PT, Ph.D.)**

Genu recurvatum has been associated with proprioception deficits and a predisposition to knee ligament injury. The primary purpose of this study was to investigate the effects of genu recurvatum on two common tests of postural control. Eleven subjects with bilateral genu recurvatum were matched with 11 controls. Force plate data were acquired while subjects were tested for steadiness during one leg standing balance and the balance leg reach test. Results failed to demonstrate a significant difference between groups except for the measure of maximum anterior-posterior sway during the functional balance leg reach test. All force plate variables indicated significant postural unsteadiness in the balance leg reach test compared to the one leg stance test. Clinicians might consider combining force plate data with functional testing to enhance the predictive value of these tests.



## **ACKNOWLEDGEMENTS**

I gratefully acknowledge Michael T. Gross, PT, Ph.D., Bing Yu, Ph.D., and Philip L. Witt, PT, Ph.D.; for all their guidance and assistance in the completion of this thesis, and throughout the course of this program of study.

Thank you to all the students and friends who volunteered as subjects for this study, for their time and interest. I want to thank my friends and classmates for their support and encouragement during the program. Most importantly, I thank my wife, Gail, for her unwavering love and support, without whom this accomplishment could not have taken place. To my children, Emily and Andrew, thank you for your understanding and patience. I love you...now let's have some fun!

## TABLE OF CONTENTS

I. INTRODUCTION .....	1
II. METHODS .....	5
A. Subjects .....	5
B. Instrumentation .....	6
C. Testing Procedure .....	6
D. Data Analysis .....	9
III. RESULTS .....	9
IV. DISCUSSION .....	11
V. CONCLUSIONS .....	21
I. APPENDIX 1: FORMS .....	34
A. Subject Questionnaire .....	34
B. Data Collection Sheet .....	35
C. Sports Activity Rating Scale .....	36
D. Instructions for Subjects .....	37
II. APPENDIX 2: REVIEW OF LITERATURE .....	38
A. Introduction .....	38
B. Tibial-Femoral Joint Stability .....	38
1. Intrinsic Factors .....	38
2. Extrinsic Factors .....	40
C. Peripheral Neural Mechanisms in Proprioception .....	41
1. Effects of Injury .....	42
2. Effects of Training .....	44
D. Joint Hypermobility .....	45
1. Grading Joint Mobility .....	45
2. Prevalence and Etiology .....	46
3. Effects of Hypermobility .....	46
E. Genu Recurvatum .....	48
F. Knee Joint in Postural Control and Function .....	50
1. Measurement of Postural Control .....	50
2. Functional Testing .....	50
G. Summary .....	52
III. Bibliography .....	56

## LIST OF TABLES

Table 1. Descriptive statistics for control and genu recurvatum group.....	22
Table 2. Intra-class correlation coefficients and mean absolute differences for test-retest reliability of the force plate measures for the one leg stance test and the balance leg reach test; and for the linear displacement measurement for the balance leg reach test.....	23
Table 3. ANOVA results assessing the effects of group (Control/Genu Recurvatum) and task (One leg stance/Balance leg reach).....	24
Table 4. Revised ANOVA to assess the simple main effects of task and group on anterior-posterior maximum sway.....	25
Table 5. Revised ANOVA to assess the simple main effects of task and group on medial-lateral mean sway speed.....	26
Table 6. Means $\pm$ SD for main effects for anterior-posterior maximum sway amplitude.	27
Table 7. Means $\pm$ SD for main effects for anterior-posterior mean sway amplitude.....	27
Table 8. Means $\pm$ SD for main effects for anterior-posterior mean sway speed.....	28
Table 9. Means $\pm$ SD for main effects for medial-lateral maximum sway amplitude.....	28
Table 10. Means $\pm$ SD for main effects for medial-lateral mean sway amplitude.....	29
Table 11. Means $\pm$ SD for main effects for medial-lateral mean sway speed.....	29
Table 12. Pearson correlation table for relationships between BLRT (Balance leg reach test) and force plate variables, for control group, genu recurvatum group, and pooled data for both control group and genu recurvatum group.....	30

## LIST OF FIGURES

Figure 1. Graph of interactions between group and task for anterior-posterior maximum sway amplitude.....	32
Figure 2. Graph of interactions between group and task for medial-lateral mean sway speed.....	33

## **I. INTRODUCTION**

Increasing numbers of people are pursuing the benefits of a healthy active lifestyle. Not all of these activities, however, are without risk of injury. A frequent site of injury or pain due to participation in recreation and sports is the knee joint. Data from one survey of over 4500 athletes in professional, Division III collegiate, high school, intramural and unorganized sports, indicate that knee injuries account for 42% of all male and 59% of all female injuries (50). Among knee injuries, damage to the anterior cruciate ligament (ACL) is common, and often devastating for an athlete.

DeHaven and Lintner (29) reported that ACL sprains alone account for 16.3% of combined male and female knee injuries. Deficiencies resulting from ACL damage include impaired knee joint proprioception (8,10), or impaired functional stability (39,76,111,116), often characterized as a feeling of the joint giving away. Joint laxity as a result of stretching or rupture of the ACL, is also associated with the risk of further joint injury and articular cartilage degeneration (4). The ability to predict injury or disability risk effectively is an important contribution to preventive healthcare.

Generalized joint hypermobility is another condition often associated with ligamentous laxity. Past research has examined the link between joint hypermobility and increased musculoskeletal complaints or articular cartilage degeneration (4,16,105). Following this reasoning, other researchers have sought to clarify the relationship between joint laxity and a predisposition for athletic injuries (22,42,67,81,89,91,125), however, these results have been controversial. One study by Brannan et al (22) found a low correlation ( $r=0.35$ ) between hyperextension and anterior knee laxity among gymnasts (22). Bird et al (16) also found that the prevalence of knee osteoarthritis in former physical education teachers who had reported hypermobility, was not greater than the control population.

Genu recurvatum, also known as knee hyperextension, is considered a common feature of knee joint hypermobility (15,24). One investigator reports that 9.8% of high

school athletes screened had unilateral genu recurvatum (2). A recent study by Loudan et al (81) indicates that genu recurvatum was a significant physical finding in 90% of female athletes in the study with unilateral ACL injury, in contrast to only 10% of the control group. Other studies investigating knee joint hypermobility among ballet dancers with generalized joint laxity have reported that subjects with genu recurvatum may have altered knee joint proprioception in the form of increased threshold to detection of motion (53), or decreased joint position sense (7). In contrast, Barrack and Skinner found ballet dancers with genu recurvatum tended to have a lower threshold to detection of motion (7). The question of whether individuals with genu recurvatum differ in functional testing of the lower extremity, or in tests of postural control when compared to those without genu recurvatum remains unanswered. Further insight into these relationships might suggest a possible deficiency in mechanical or neuromuscular control of the knee.

Impaired joint proprioception following ligament sprain has been investigated for both the ankle and knee (7,10,38,51,75). The typical assessment of proprioception involves non-weight bearing procedures, however, the association between non-weight bearing tests and functional ability is not clear (1,58). Clinicians frequently use weight-bearing tests because they may reflect functional activity more accurately. Recently, Anderson (1) compared functional, weight-bearing tests of knee joint flexion angle reproduction, to the typical non-weight bearing assessment of proprioception and found that knee joint angles were more accurately reproduced in weight bearing. Therefore, an accurate weight bearing test of proprioception could be beneficial.

Functional knee joint tests typically involve dynamic weight bearing activities. Functional tests are considered helpful in determining an athlete's ability to return safely to sport or activity following a ligament injury. Although reliability has been investigated for several of the tests (20), the predictive validity of many of these tests is somewhat questionable (6,95,111,116). Barber et al (6) reported that 50% of ACL deficient patients performed normally on the one legged hop test, although all reported functional instability with sports. Another functional test is the balance-leg-reach test. In this test, subjects balance on the affected leg while the distance they extend the other foot forward is measured. Greenberger (48) examined this test along with two additional lower extremity

tests, and has reported the intraclass correlation coefficient is between 0.73 and 0.91 for this test.

Another type of functional testing, known as stabilometry, uses a force plate to assess functional instability. Common measures of stability such as center of pressure variability are used to assess the effects of an injury on an athlete's postural control. These tests usually compare the injured and uninjured extremity (37,45), or compare injured to uninjured athletes (26,39,117). The relationship between most functional tests of lower extremity control and postural control, however, is not clear.

Clinical measures of postural control are commonly used to assess patients with neurological problems, or problems related to falls in the elderly (14,32,34). Methods of assessing postural control include timed standing balance tests (17), functional reach tests (14), and force plate tests which quantify postural steadiness (30,43,90). Force plate data can be used to determine variation in center of pressure, or ground reaction forces and moments of force. Such information can be used to quantify balance or lower extremity neuromuscular function. The use of the force plate to assess joint stability has been described extensively in studies of reported functional instability associated with ankle ligament injury and laxity (26,37,45,117,118), and to a lesser degree in studies of knee stability (39,55,88,127). Although simpler clinical tests of postural control do exist, the objectivity and sensitivity of these tests is somewhat controversial, and the results do not generalize well to a healthy younger population (14,18). Further insight into the use of the force plate as a valid and objective measure of knee joint stability could provide valuable information regarding an athlete's safe return to sport.

A valuable clinical test should be valid, reliable, and sensitive. In a translated (120) portion of a report written by M.H. Romberg in 1851, the procedure he used for assessing balance reveals the simplicity and validity of this early clinical test. The sensitivity of the Romberg test, however, is questionable. Several investigators have examined the relationship between clinical assessments and functional performance or outcome (6,10,57,111). Snyder-Mackler et al (111) found measures of anterior laxity in ACL deficient subjects did not relate to functional outcome. Harter et al (57), likewise, found

both instrumented measurements of joint laxity as well as clinical orthopedic tests correlated poorly with patient perceived outcomes.

Because genu recurvatum is not always associated with a prior ligamentous injury, individuals with this condition may not be as carefully screened during pre-participation examinations as might someone with an existing ACL injury. Similarly, these individuals may not demonstrate deficiencies when tested by traditional functional testing methods. A sensitive, objective, and reliable test of balance could provide useful information in settings with significant populations of active younger clients.

Because of the incidence of knee injuries in the active population, and the suggested association between joint hypermobility and predisposition for knee injury, effective methods of screening for risk factors is important. The primary purpose of this research was to compare two groups of college age individuals to determine whether subjects with genu recurvatum perform differently than controls on force plate measures of postural control, and on a functional test of lower extremity control. The secondary purposes were to determine the association between force plate measures of postural control and a functional measure of lower extremity control, and to determine the reliability of these two methods of measurement.

The specific research questions addressed are:

1. Do subjects with genu recurvatum differ from controls in force plate measures of postural control for the one-leg stance test and the balance leg reach test?
2. Do subjects with genu recurvatum differ from controls in performing the balance leg reach test of lower extremity control?
3. Is there an association between force plate measures of postural control and the linear displacement measure of the balance leg reach test?
4. What is the test-retest reliability of force plate measures for the one leg stance test and the balance leg reach test, and for the linear displacement measure of the balance leg reach test?



## **II. METHODS**

### **A. Subjects**

All subjects were recruited from students and faculty of the University of North Carolina, Chapel Hill. The age range was from 18-37 years (mean =  $27.6 \pm 5.3$ ). A preliminary screening determined whether subjects had a condition that affected their balance or were taking any medication that may have dizziness or balance difficulty as a side effect. Prior to testing, all subjects completed an interview and a brief questionnaire regarding health history, type and frequency of exercise, and any activity related knee pain. This information was used for demographic data, inclusion/exclusion criteria, and to assess for generalized joint hypermobility and activity level (94). Height (0.5cm) and weight (0.5kg) were measured. All subjects were screened for normal knee strength based on their ability to balance on one leg and squat to  $< 70^\circ$  of knee flexion while holding a weighted box. All subjects demonstrated at least  $10^\circ$  ankle dorsiflexion bilaterally when doing the squat testing. Eleven individuals with bilateral genu recurvatum were selected as subjects based on the supine goniometric method for measuring recurvatum. These subjects also demonstrated at least  $10^\circ$  of genu recurvatum bilaterally. The control group consisted of 11 age ( $\pm 5$  years), gender, and activity matched individuals. Subjects in the control group did not have bilateral knee joint genu recurvatum, other knee joint pathology, or balance deficits.

Exclusion criteria for all subjects included: history of knee ligament surgery, ankle surgery, knee, ankle, hip, or back injury within the past 6 weeks; musculoskeletal injury within the month prior to testing which altered normal activity for more than two days; known or diagnosed balance condition or use of medication that affects balance; participation in exercise 2 hours prior to testing; alcohol consumption for 24 hours prior to testing; and the need to wear bifocals. Subjects were also assessed for generalized joint hypermobility. Prior to testing all subjects signed statements of informed consent.

## **B. Instrumentation**

A Bertec Model 4060A (Bertec Corporation, Worthington, OH) force plate mounted in the floor was used to measure the center of pressure of the foot during the two standing tasks. DATAPAC III (Run Technologies, Laguna Hills, CA) software on a 486-PC acquired data online, and was used to transform data files. A customized computer program by Motionsoft © (Chapel Hill, NC) calculated the center of pressure measures. A strip of computer data paper marked with lines was used to measure the linear displacement (0.5cm) of a standard shoe box measuring 19cm (width), by 10.5cm (height), and 29.5cm (length), during the balance-leg-reach test. The box was weighted with twelve ounces of weight to prevent unwanted sliding on the computer paper. A standard clinic scale was used to measure subjects' height and weight. A standard goniometer with a two degree scale was used to measure knee joint angle while the subjects were supine.

## **C. Testing Procedure**

During the screening phase, all subjects were tested for joint hypermobility using the Carter and Wilkinson index (24), as modified by Beighton et al (13). This index (range 0-9 points) is based on assessment of 5<sup>th</sup> finger MCP joint extension  $>90^\circ$ , elbow extension  $>0^\circ$ , knee extension  $>10^\circ$ , and the ability to place the hands flat on the floor when bending the back with the knees straight. All subjects were also tested for normal bilateral knee strength as defined by the ability to squat to approximately  $70^\circ$  of knee flexion in unilateral stance while holding a box containing weight equal to 15% of their body weight for females, and 25% for males. This criterion was established based on preliminary testing of four healthy men and four healthy women, and selecting the lowest weight that each group could manage during this test.

All subjects and controls were assessed for postural steadiness without shoes during one leg standing balance on the force plate. Subjects were given specific instructions in the requirements of the task. Each subject was asked to stand as still as possible in the center of the force plate. Each subject was required to balance on one foot for 15 seconds with eyes open and focused on a visual target on a wall 20 feet away. The

feet were oriented in the direction of the long axis of the force plate (Y direction). Subjects were given the command "ready, set, go." On the command "ready", each subject assumed the position of hands on the iliac crest and looked at the target. On the command "set", subject raised the heel of the non-weight bearing foot. Finally, on the command "go", the contralateral knee and hip were flexed so that the foot was two to three inches above the force plate, but not touching it. Data acquisition commenced on the "go" command and ended following a timed period of 15 seconds. Subjects were tested for three acceptable trials on each leg, alternating legs between trials. The interval between testing of the same leg was approximately one minute. If the subject touched the floor or force plate with the non-weight bearing foot, the trial was repeated until three acceptable trials were obtained for each lower extremity. The total number of trials required was recorded. Prior to the start of the second task, subjects rested for approximately 2 minutes.

All subjects were also assessed on a functional test of lower extremity control. The balance leg reach test was performed with the subject standing without shoes, and with the second toe of the weight bearing leg aligned on a mark at the center of the front edge of the force plate. Subjects were given specific instructions in the execution of the second task, and allowed to practice the task three times prior to the start of testing. The subject was instructed to push the shoe box forward as far as possible with the contralateral foot while maintaining balance on the weight bearing leg, and then return to bilateral standing. Subjects were again given the command "ready, set, go." On the command "ready", the subject assumed the position of hands on iliac crests, and raised the heel of the contralateral foot. On the command "set", the foot was raised off the floor. Finally, on the command "go", the foot contacted the box and data acquisition was begun. The exact strategy of pushing the shoe box forward was left to subject choice, although subjects were not allowed to kick the box forward. The subject was required to maintain contact between the shoe box and the non-weight bearing foot during the entire period for forward translation of the shoe box. Data acquisition ended when both feet rested on the force plate again. The subject performed three trials on each weight bearing leg, alternating between trials. Approximately one minute delay occurred between each trial

on either leg while the examiner measured the distance the box was moved. If the subject touched the floor with the outstretched foot the trial was repeated until three acceptable trials were obtained for each lower extremity. The total number of trials required were recorded. The investigator recorded the linear distance (to within 0.5cm), that the box was pushed from the front edge of the force plate. The box was marked with a dot in the center of the lower front edge. The displacement of the box was recorded as the linear displacement of this point in reference to the horizontal lines on the computer paper, which was taped to the floor. Force plate data were acquired simultaneously for three trials on each leg, as for the one leg stance test. The linear measure of the balance leg reach test was subsequently normalized to the subjects' height.

Force plate data were sampled at 20hz, and converted with the Datapac A-D converter. A software program (Motionsoft ©) on a Pentium computer calculated the mean center of pressure from the digital data. The following parameters were then determined from the center of pressure data: 1) maximum sway (peak to peak amplitude) (mm) of the center of pressure in the anterior-posterior and medial-lateral directions; 2) the mean sway (mean of absolute value of all variations of center of pressure from the mean center of pressure) (mm) in the anterior-posterior and medial-lateral directions; 3) the mean speed (mean instantaneous speed) of center of pressure variation in anterior-posterior and medial-lateral directions; 4) the total travel distance (mm) in the anterior-posterior and medial-lateral directions over the 15 second test interval. The last variable was recorded for the one leg stance test only, due to the variability in the time interval used by subjects to perform the balance leg reach test. The force plate linear data were also normalized to subject height.

Nine subjects, including four from the control group and five from the genu recurvatum group were recruited to perform the testing a second time, following a five minute rest period. One additional subject from the control group repeated testing one week later. These data were used to test the reliability of the tests.

#### **D. Data Analysis**

Force plate data were processed using the force plate software. Center of pressure measures from 3 acceptable trials for each leg during the one leg stance test, and the balance leg reach test were averaged. The mean of the measure for both legs was then averaged to describe the performance measure for the test. Center of pressure displacements were normalized to the subjects' height. The differences between groups for the six force plate variables for the two tasks were then analyzed using two-way analysis of variance (ANOVA) with group and task as the two factors. An independent samples t-test was used to compare groups on the normalized linear measurement of the balance leg reach test, and on the total travel distance for the one leg stance test. Pearson correlation coefficient analysis was used to compare the linear measure of the balance leg reach test with the force plate variables. Intraclass correlation coefficients were computed for test-retest reliability of the two testing methods. The mean absolute differences were calculated for the test-retest variables, to further clarify the reliability of the tests. The variance of the force plate measures and the variance of the balance leg reach test scores between the two occasions were compared. Post hoc power analyses were computed for the dependent variables.

### **III. RESULTS**

Descriptive statistics are presented for the two groups in Table 1. The t-tests revealed no significant differences between groups, with the exception of the mean joint hypermobility score and the mean genu recurvatum measurement. Both of these variables were greater for the genu recurvatum group.

Intraclass correlation coefficients (ICC), form (3,1), were computed for the comparison of performance results between the initial test, and a second test conducted after a five minute rest period (107). The ICC ranged from a high of 0.94 for the balance leg reach test across trials, and a high of 0.94 for the mean medial-lateral speed variable on the one leg stance test, to a low of -0.11 for the medial-lateral maximum sway variable on the one leg stance test (Table 2). The ICC values were appreciably greater for the balance leg reach test than for the one leg stance test. The mean absolute differences revealed

relatively little variation between testing sessions. The mean absolute differences for all variables were less than one standard deviation of the mean value for the variable.

The two-way ANOVA procedures revealed a significant interaction between group and task for the anterior-posterior maximum sway and the medial-lateral mean speed variables (Table 3). These interactions were further analyzed for simple main effects (Tables 4-5). The analysis for anterior-posterior maximum sway showed that the means for the two tasks were significantly different for the control group: 1.37 for the one leg stance test, and 4.35 for the balance leg reach test. The anterior-posterior maximum sway values for the two tasks were also significantly different for the genu recurvatum group: 1.29 for the one leg stance test, and 3.64 for the balance leg reach test (Fig 1). The anterior-posterior maximum sway values were also significantly different between groups for the balance leg reach task: 3.64 for the genu recurvatum group, and 4.35 for the control group. The analysis for medial-lateral mean speed showed that the means for the two tasks were significantly different for the control group: 1.69 for the one leg stance test, and 3.04 for the balance leg reach test. The medial-lateral mean speed for the two tasks was also significantly different for the genu recurvatum group: 1.65 for the one leg stance test, and 3.54 for the balance leg reach test (Fig. 2).

For the remainder of the force plate variables: anterior-posterior mean sway, anterior-posterior mean sway speed, medial-lateral maximum sway, and medial-lateral mean sway, a significant main effect was present for the task (Tables 6-11). The balance leg reach test values were greater than the one leg stance test values for all of the force plate variables.

The group means (SD) for the linear displacement of the box during the balance leg reach test were 0.40 (0.02) for the control group, and 0.39 (0.03) for the genu recurvatum group. These values were not significantly different. These normalized linear displacement values represent an average distance on the balance leg reach test that was 39-40% of the subject's height. The comparisons of group means for the anterior-posterior and medial-lateral total travel distances during the one leg stance test were also not significantly different. For this variable, the mean (SD) for anterior-posterior total travel distance during the 15 second sampling period was 23.19 (3.68) for the control

group and 24.4 (7.52) for the genu recurvatum group. The values in the medial-lateral direction were 26.42 (3.83) for the control group and 26.45 (6.10) for the genu recurvatum group.

The correlational results in Table 12, were screened for relationships between the balance leg reach test linear displacement and the force plate variables. The correlations for the data pooled across both groups showed a moderate relationship between the balance leg reach test and anterior-posterior maximum sway ( $r = 0.62$ ,  $p < 0.05$ ), and a low correlation ( $r = 0.43$ ,  $p < 0.05$ ) between balance leg reach test and anterior-posterior mean sway. The data for the control group showed a moderate relationship between the balance leg reach test and anterior-posterior maximum sway ( $r = 0.70$ ,  $p < 0.05$ ). The data for the genu recurvatum group showed no significant relationships between the balance leg reach test and any of the force plate variables.

A post hoc power analysis was computed to determine the power of the test to detect significant differences between the groups (25). The power values ranged from 0.0 to 0.49 for the variables across both tests.

#### **IV. DISCUSSION**

The primary interest for this paper was to evaluate one biomechanical component of postural stability, in particular that portion associated with the knee. For this study, the operational definition of stability was the ability to maintain the center of pressure in a position with minimal variation. Another aspect of this investigation was to assess the sensitivity of the force plate measures of steadiness in quantifying differences at the knee joint under two different task conditions. The selection of the one leg stance test for assessing postural control was based in part on previous studies (30,32,37), and in part on clinical observations that individuals with genu recurvatum had a tendency to stand in the "back-knee" position. The assumption was that the difference in postural stance might manifest as a quantifiable difference in force plate output when assessing postural control. The balance leg reach is a more dynamic functional task that was selected because of its popular use in the clinical setting, and for the reported reliability (48) and sensitivity of the test in assessing ACL deficiency (101).

Force plate testing is often used to assess postural control, and frequently the one leg stance test is part of the testing procedure. Scant evidence exists, however, concerning normative data for this test. Normative data have been published for males and females aged 20-64 (30), for men in 3 age groups (32,90), and for 76 year old adults (34). The data from this study were normalized to subject height for all analyses. The non-normalized data were compared with data from previous researchers who did not normalize their data to height. Since force plate variables are not always the same among these studies, and are not always defined similarly among studies, comparisons are difficult to make.

One measure that was comparable between this study and previous studies was the anterior-posterior mean sway amplitude for the one leg stance test. The anterior-posterior mean sway amplitude over all subjects for the current study was 0.6 cm, compared to 0.55 cm for the 20-29 year old group (values for males and females averaged) reported by Ekdahl et al (30). Good agreement between these two studies exists for the medial-lateral mean sway amplitude, with 0.55 cm in the current study and 0.4 cm (values for males and females averaged) in the Ekdahl study (30). For the present study the mean anterior-posterior speed of the center of pressure was 2.3 cm/sec and the mean medial-lateral speed was 2.8 cm/sec. Ekdahl et al (30) reported the center of pressure velocity along a sway path that was directionless, and averaged 2.95 cm/sec. The data from the present study also showed some agreement with Murray et al (90) regarding the anterior-posterior and medial-lateral travel distance, with 26.4 cm and 29 cm for the two directions in the current study, compared to 31.5 cm and 34.5 cm, respectively, reported by Murray et al (90). The anterior-posterior (21 cm) and medial-lateral (23 cm) travel distances from this study were also normalized to the same time period used by Era et al (32). Distances were only somewhat similar with the extent of sway (14.5 cm anterior-posterior, and 13.5 medial-lateral) reported for the 31-35 year old men in their study. Other investigators presenting reference data either used different calculations, or used bilateral standing balance in their normative studies.

The lack of statistically significant differences between the groups in this study may be due to several factors: 1) no differences exist between the two groups; 2) the



magnitude of the intrasubject variability; 3) the lack of sensitivity of the testing; 4) the lack of power of the test to detect significant differences. Each of these factors will be addressed in turn.

The two groups in this study may truly not differ from one another on the variables measured. The literature suggests that genu recurvatum may be associated with altered proprioception (7,53) and a predisposition to ACL injury (81), although these studies have not been replicated. The fact that a group difference existed on the force plate measure of anterior-posterior maximum sway may be an isolated finding. It is interesting to note, however, that although no significant differences existed on most of the variables, two trends appeared in the data: four of the six variables measured on the balance leg reach test were greater for the genu recurvatum group than the control group (Tables 8-11), and all of the variables on the one leg stance test were equal or less for the genu recurvatum group than the control group (Tables 6-11). Whether this trend suggests a difference in light of the statistical evidence is not clear, however, the variance on all the measures was greater than the calculated mean absolute differences for the test-retest reliability. These issues may warrant further investigation.

The lack of significant differences may be due, in part, to the magnitude of intrasubject variability. Several investigators have reported on the degree of variability of center of pressure measures under conditions of quiet standing (20,41,90,97). Intrasubject variation in two legged stance was examined by Geurts et al (41) using the coefficient of variation (defined as standard deviation of the parameter divided by the mean x 100). These investigators reported coefficient of variation values for anterior-posterior and medial-lateral peak to peak amplitude of 25% and 25%, respectively for a 22-30 year old group (n=8). For the current study the computation for coefficient of variation yielded values of 23% and 35% for the same parameters. Applying this formula to the data for the Ekdahl study (30) yields coefficients of variation of 26.5% for the mean anterior-posterior sway, and 25% for the mean medial-lateral sway. These values compare to 22% for the mean anterior-posterior sway amplitude, and 18% for the mean medial-lateral sway amplitude for the current study. Computing coefficient of variation for the data reported by Murray et al (90) yields 31% for anterior-posterior and 22% for medial-lateral mean

sway. Although the comparison with Geurts et al (41) may not be warranted, the comparison between the current study and that of Ekdahl et al (30) showed strong agreement on the mean anterior-posterior coefficient of variation values. The current study, however, does not show the same level of agreement for the medial-lateral sway as did the other two studies. Therefore, the lack of group differences reported here may reflect the fact that normal postural sway as measured by the force plate may be greater than the sum of the possible effects that genu recurvatum may have imposed.

In addition to the within subjects variability issue, subjects in the genu recurvatum group, as a whole, did not stand in the “back knee” position during the one leg stance test as expected. The observed stance posture of the weight bearing knee actually appeared to be near the neutral position of the knee joint, or in some instances in slight knee flexion. This balance strategy may have been selected because single leg stance is more demanding than bilateral stance (30,43), thus, requiring more conscious effort in an attempt to control the joint, or it may simply be a more stable position of the knee during one legged stance. Schenkman (104) suggests that the effect of joint constraint or impairment may result in mechanical limitations to postural control. Maintaining the knee joint locked in a position of hyperextension may impose a constraint to postural control, thus, making this an inefficient strategy for one leg balance. While every subject was given the same specific instructions for each task, the choice of balance strategy was otherwise left up to the individual subject.

The issues of test reliability and sensitivity are of paramount concern in this study. The use of the force plate to assess joint stability has been described extensively in studies of reported functional instability associated with ankle ligament injury and laxity (26,37,45,117,118), and to a lesser degree in studies of knee joint stability (39,55,88,127). Although simpler clinical tests of postural control exist, the objectivity and sensitivity of these tests is somewhat controversial, and the results may not generalize well to a healthy younger population (14,18). Other investigators have not reported the reliability of their tests. Friden et al (39) reporting on the standard deviation of the center of pressure variation, noted that the number of oscillations exceeding 5 mm and 10 mm and the average speed of oscillations were significantly greater in 19 subjects with ACL

insufficiency than a control group. Mizuta et al (88) used center of pressure measures of sway area and length of sway path to demonstrate greater unsteadiness in a group of ACL deficient subjects who had functional instability associated with cutting sports. Neither of the two previous studies reported on the reliability of the testing. In contrast to the former two investigations, Harrison et al (55) were unable to demonstrate differences in a center of pressure dispersion index between the healthy leg and the ACL reconstructed leg in subjects 10-18 months post surgery. This subject group, however, had balance training as part of their rehabilitation program. Harrison et al (55) examined reliability by establishing correlation coefficients for observed obtained scores and an instrumented method of assessing balance. Correlation coefficients were low, ranging from 0.38 to 0.45 (55).

As noted previously, the ICC's ranged from -0.11 to 0.94 for the two tasks performed in the current study. The fact that the force plate parameters had greater overall ICC values for the balance leg reach task may suggest that there is less variation in the performance of this task than for the one leg stance task. This statement is supported by the nearly invariant averaged values for the linear displacement of the box being 39% to 40% for both groups. The mean absolute differences, however, showed a trend toward being greater and more variable for the balance leg reach test than for the one leg stance test. The ICC of 0.94 for the balance leg reach task itself was greater than that reported by Greenberger et al (48) as between 0.73 and 0.91. The test-retest coefficients for the one leg stance task parameters of anterior-posterior total travel distance (0.78) and medial-lateral travel distance (0.70) from the current study agree, in part, with those reported by Ekdahl et al (30) for right (0.65) and left (0.72) leg on length of sway path. In contrast, Goldie et al (43,44) have reported reliability values for anterior-posterior center of pressure on the preferred foot of 0.49 and 0.47 in separate studies. These same investigators also reported values of 0.76 and 0.60 for reliability of medial-lateral center of pressure, for preferred and non-preferred limbs during one leg stance (44). The issue of reliability should be addressed in future studies.

If any statistically significant differences existed between groups in the current study with regard to postural control they were not demonstrated by the one leg stance task. The only variable for which significant group differences were present was the force

plate measure of anterior-posterior maximum sway. This variable was statistically different for the two groups on the balance leg reach task, as revealed in the analysis of simple main effects. The reader should consider the modest reliability level of the ICC (0.74) for the anterior-posterior maximum sway measure on this test. Of additional interest is the fact that the control group had a larger value (4.35) than the genu recurvatum group (3.64) for this functional test of lower extremity control. It could be argued that this signifies a performance measure, and that the control group had a greater range of control in the anterior-posterior direction. The lack of differences in the linear measure of the balance leg reach test, however, questions this assumption. This finding may suggest the control group did not demonstrate the same degree of neuromuscular control in the anterior-posterior direction that the genu recurvatum group did for this task. This result may also suggest the genu recurvatum group may have developed a compensatory level of neuromuscular control due to their joint hyperextension condition. Previous research has indicated that fluid distention (71), or traumatic stretching of joint tissues containing mechanoreceptors adversely affects the stability of the joint (37). Whether people with genu recurvatum have functional instability as a result of overstretched ligaments or joint capsule is not clear. It is questionable, however, whether this dynamic test, performed in the range of knee joint flexion required, would be effected by stretched posterior joint tissues.

The power values computed for the variables clearly identify a lack of statistical power as an issue in this study (25). Given the slight variability between groups for the measured parameters, the power to detect a significant difference was, at best, 0.49 for the one test that demonstrated significant group differences. A preliminary power analysis may have been helpful in designing aspects of this study. Researchers should consider the variability of these test parameters in the design of future studies.

The finding that these groups differed on a force plate parameter during the balance leg reach task may be somewhat more significant in light of the fact that the t-test for the linear displacement of the box was not different between the two groups. This result may indicate that indeed there was no difference between groups on this test. This finding might also suggest that force plate measurements obtained simultaneously with this

functional test might add a dimension of sensitivity that is not present in the balance leg reach test measured by linear displacement alone.

The results of this study may support the use of the balance leg reach test in discriminating differences in postural control. In agreement with Harrison et al (55), it appears that the predictive value of the one leg stance test is weakened due to a lack of sensitivity in a population of this type. The values for all force plate variables were greater for the balance leg reach test than they were for the one leg stance test. The results tend to suggest that the neuromuscular demands required for the balance leg reach test are greater than those required for the one leg stance test. This task may also be more appropriate for assessing certain aspects of postural control. As Horak (60) has reported, several functional components exist for postural control, including the biomechanical, the motor coordination, and the sensory organization components. Clinicians may wish to consider this task, or a similar functional task, when attempting to elucidate subtle postural control problems. Further investigation into the usefulness of such a test with other populations also may be warranted.

The results of the correlation analysis for the balance leg reach task and the force plate measures revealed few significant relationships. The weak to modest values for anterior-posterior maximum sway and anterior-posterior mean sway in the pooled data and control group data, were not present in the genu recurvatum group data. This result could be explained by the fact that the linear displacement measure was relatively invariant across the two groups, whereas, many of the force plate measures showed greater variability. Another consideration is that given the range of motion within which the balance leg reach task occurs, the force plate center of pressure measurement may be inappropriate for describing joint stability. Further analysis of this task using force measures and a more restricted protocol could be beneficial.

Functional knee joint stability testing for athletes typically involves dynamic weight bearing activities. Functional tests are used to help determine if an athlete can return safely to sport or activity following a ligament injury. The predictive validity of many of these tests has been questioned (6,95,111,116). Recently, however, investigators have found that the value of functional tests in predicting performance improves when more

than one test is used (95). The results of this study confirm, in part, that both the one leg stance test and the linear balance leg reach test alone were insufficient to discriminate between groups. Differences between groups, however, may be so small as to be insignificant in a sample of this size. Perhaps when used in conjunction with other types of performance tests, force plate balance or postural control tests may add a degree of sensitivity that may be valuable in discriminating subtle insufficiencies. Further insight into the use of force plate measures as a valid, reliable and objective means to assess knee joint functional stability could prove valuable, for example, regarding the appropriate timing for returning an athlete to sport.

Regarding the underlying issue of whether individuals with genu recurvatum have altered proprioception, this study failed to provide evidence that this was the case. Although the effects of genu recurvatum on knee joint proprioception have been investigated, the results are inconclusive (7,53). The intent of this study was not to examine proprioception between these two groups, however, the study may have benefitted from a preliminary test of proprioception to help clarify the impact of that component of joint stability and control on the postural tests used in this study. Additional testing of individuals with genu recurvatum may contribute to better understanding the relationship between proprioception and postural stability in a similar group. This study may also have benefitted from additional screening to assess subjects' preferred method of standing. Although the author has observed numerous individuals who stand in the "back-knee" stance, subjects were only briefly observed in the sagittal plane prior to testing the squat lift. The hyperextended knee is thought to allow individuals to "hang" on their posterior ligaments and joint capsule requiring less muscular activity, but at the risk of over-stretching the posterior aspects of the joint. Perhaps assessing these two groups in bilateral stance may have helped demonstrate differences in center of pressure variation that was not evident in one leg stance.

The question of whether proprioception is the same in weight bearing as in non-weight bearing has also recently been addressed (1,58). In both studies the authors concluded that joint angle replication was better in weight bearing. Conversely, Barrak et al (9) have argued that joint angle replication is a less sensitive measure of proprioception

than threshold to detection of joint movement. Subtle differences in proprioception may be eliminated during weight bearing tasks. Perhaps more dynamic tests of knee joint control or the inclusion of a perturbation element to this study may have been useful in distinguishing the possible differences in these two groups.

The nature of neuromuscular control of posture and joint stability involves both static and dynamic elements. Information gathered from muscle, tendon, ligaments and the joint itself is processed and utilized both volitionally and reflexively. A recent study by Huston and Wojtys (64) was conducted to identify predisposing neuromuscular factors for knee injuries. This well conceived study revealed some of the differences between female athletes and controls and between female and male athletes. Among the differences cited were those regarding muscular strength, endurance, and motor recruitment order (64). Although the relationship between strength and performance is not always clear, the use of normative strength values may have provided additional information about whether these two groups differed from reference values (19). All subjects were required to lift a weighted box during a one leg squat test as part of the screening for "normal lower extremity strength. Additional testing of lower extremity strength using a dynamometer to test the quadriceps and gluteal muscles may have revealed differences in other aspects of lower extremity strength that would help clarify the issue of neuromotor control. Further quantification of relative muscular output, such as electromyography (EMG), during these two tasks may also have been helpful. Whether balance or motor control is altered in individuals with genu recurvatum is not known. Some evidence suggests that individuals with genu recurvatum may be at risk for possible ACL injury (81). Clinical observations of skeletally immature adolescents, have also shown that genu recurvatum is associated with a greater incidence of patellar subluxation. These issues require further study.

The selection of appropriate force plate parameters to assess a specific problem or condition has been discussed in the literature (100). Goldie et al (43) have suggested that force measures are more sensitive than center of pressure measures. Geurts et al (41), however, have argued that the former study did not utilize any frequency dependent measures. Some investigators have also suggested that highly correlated force plate measures may be redundant, simply measuring the same attribute of balance (100). A well

conceived study by Prieto et al (100) compared younger and older adults under eyes open and eyes closed conditions of bilateral stance, using a multitude of common and "hybrid" force plate parameters. These authors concluded that multiple types of force plate measures are necessary to adequately characterize differences between groups. The inclusion of maximum sway, mean sway and mean speed of sway in this study was intended to provide a variety of measures to help describe the groups adequately.

Previous literature suggests an association between balance, proprioception, and joint laxity. This study was intended to probe into the nature of postural control and functional knee joint stability, by examining two similar groups, one having a postural fault and the other not having the same postural fault. The fact that additional measures were not statistically significant may relate to the sample size and the small differences in the force plate measures. A power analysis conducted prospectively would have dictated the use of a larger sample size. Further research into the nature of the relationship between balance, proprioception, and strength and joint stability could provide the data needed to clarify these issues.

Studies of this type should continue to utilize common measurement methods in order to create a data-base of reference values. Future studies might also examine more demanding functional tasks using force plate measurement with similar case controlled groups to help determine whether individuals with genu recurvatum or other non-traumatic joint laxity are at risk for ligament injury while participating in sports.

The results of this study may not generalize to all populations. The literature supports a trend that many loose-jointed children tend to become less mobile as they age. Whether the subjects in this study are unique in that they continue to have genu recurvatum at this age is not clear. Since all subjects examined were recreational athletes, or moderate exercisers, application of these results to a more highly trained athlete is diminished. This study examines one aspect of postural control, and one functional test of lower extremity control. No test is known which is a "gold standard" for these constructs. This study is therefore limited to two frequently used clinical methods of assessment, which may not be universally acceptable.



## **V. CONCLUSION**

No differences were found in postural control measures during quiet one leg stance between a control group and a group with genu recurvatum. The genu recurvatum group had a lower mean value on the force plate measure of anterior-posterior maximum sway for the balance leg reach task than the control group. Statistically significant differences between tasks for both the control and genu recurvatum group on all the force plate measures, indicate the balance leg reach task placed greater demands on postural control than did the one leg stance task. One trend that was evident is that the control group had greater anterior-posterior maximum sway. Whether these findings indicate a difference in neuromuscular control associated with the genu recurvatum group is not known. The values obtained on the linear displacement task suggest that measurements normalized to height may be approximately 40% for subjects of this age with no history of knee ligament surgery.

<b>Variable</b>	<b>Control Group (n =11)</b>	<b>Genu Recurvatum Group (n =11)</b>
Gender (male/female)	3/8	3/8
Age (yrs)	27.9 (5.32)	27.4 (5.54)
Height (m)	1.67 (0.09)	1.69 (0.13)
Mass (kg)	63.0 (10.95)	67.4 (18.85)
Mobility Score*	2.82 (2.14)	5.27 (1.85)
Genu Recurvatum* (degrees)	3.91 (3.5)	12.77 (2.3)
Activity Level (1>4)	1.9 (0.54)	1.9 (0.54)

\*p<0.05 Values for genu recurvatum group significantly greater than those for control group.

**Table 1.** Descriptive statistics for control and genu recurvatum groups. Values are mean (SD) Mobility score = number of joints scored as hypermobile using 0-9 rating scale.

Variable	One Leg Stance Test		Balance Leg Reach Test	
	ICC	Mean Absolute Difference $\pm$ SD	ICC	Mean Absolute Difference $\pm$ SD
Anterior-posterior maximum sway	0.44	0.25 (0.23)	0.74	0.39 (0.52)
Anterior-posterior mean sway	0.76	0.04 (0.04)	0.91	0.11 (0.08)
Anterior-posterior mean speed	0.46	0.23 (0.16)	0.91	0.38 (0.45)
Anterior-posterior travel distance	0.78	2.40 (2.48)	---	---
Medial-lateral maximum sway	-0.11	0.36 (0.32)	0.66	0.70 (0.71)
Medial-lateral mean sway	0.60	0.03 (0.02)	0.79	0.18 (0.18)
Medial-lateral mean speed	0.94	0.15 (0.16)	0.88	0.31 (0.28)
Medial-lateral travel distance	0.70	2.63 (3.21)	---	---
Balance leg reach test			0.94	0.01 (0.007)

**Table 2.** Intra-class correlation coefficients and mean absolute differences for test-retest reliability of the force plate measures for the one leg stance test and the balance leg reach test; and for the linear displacement measurement for the balance leg reach test.

Variable	Group (df 1,20)	Task (df 1,20)	Group x Task (df 1,20)
Anterior- Posterior Maximum Sway	4.73*	490.16*	6.79*
Anterior- Posterior Mean Sway	1.36	314.56*	0.07
Anterior- Posterior Mean Speed	1.17	146.30*	1.85
Medial- Lateral Maximum Sway	0.26	36.41*	2.14
Medial- Lateral Mean Sway	1.27	25.00*	1.54
Medial- Lateral Mean Speed	1.33	165.84*	4.65*

\*p<0.05

**Table 3.** ANOVA results assessing the effects of group (Control/ Genu Recurvatum) and task (One leg stance/ Balance leg reach). Values are F statistics obtained for all analyses.

\*p<0.05

Source	df	SS	MS	F
Task at Control	1	48.66	48.66	304.13*
Task at Genu-recurvatum	1	30.35	30.35	189.69*
Task x Subjects (group)	20	3.18	0.16	
Group at One Leg Stance	1	0.05	0.05	0.19
Group at Balance Leg Reach	1	2.80	2.80	10.37*
Pooled Error	40	10.68	0.27	

\* $p < 0.025$

**Table 4.** Revised ANOVA to assess the simple main effects of task and group on anterior-posterior maximum sway.

Source	df	SS	MS	F
Task at Control	1	9.76	9.76	57.41*
Task at Genu-recurvatum	1	19.53	19.53	114.88*
Task x Subjects (group)	20	3.47	0.07	
Group at One Leg Stance	1	0.01	0.01	0.03
Group at Balance Leg Reach	1	1.45	1.45	4.67
Pooled Error	40	12.42	0.31	

\*p<0.025

**Table 5.** Revised ANOVA to assess the simple main effects of task and group on medial-lateral mean sway.

	One Leg Stance Task	Balance Leg Reach Task	Group Mean
Control Group	1.37 ± .034	4.35 ± 0.76	2.86 ± 1.63
Genu Recurvatum Group	1.29 ± 0.28	3.64 ± 0.54	2.46 ± 1.27
Task Means	1.33 ± 0.31	3.99 ± 0.74	

**Table 6.** Means ± SD for main effects for anterior-posterior maximum sway amplitude.

	One Leg Stance Task	Balance Leg Reach Task	Group Mean
Control Group	0.40 ± 0.10	1.68 ± 0.28	1.04 ± 0.68
Genu Recurvatum Group	0.35 ± 0.04	1.58 ± 0.35	0.96 ± 0.68
Task Means	0.37 ± 0.08	1.63 ± 0.31	

**Table 7.** Means ± SD for main effects for anterior-posterior mean sway amplitude.

	One Leg Stance Task	Balance Leg Reach Task	Group Mean
Control Group	1.37 ± 0.27	3.68 ± 0.67	2.53 ± 1.28
Genu Recurvatum Group	1.37 ± 0.36	4.26 ± 1.39	2.81 ± 1.78
Task Means	1.37 ± 0.31	3.97 ± 1.10	

**Table 8.** Means ± SD for main effects for anterior-posterior mean sway speed.

	One Leg Stance Task	Balance Leg Reach Task	Group Mean
Control Group	1.49 ± 0.54	2.60 ± 0.87	2.04 ± 0.91
Genu Recurvatum Group	1.28 ± 0.35	3.11 ± 1.47	2.20 ± 1.40
Task Means	1.38 ± 0.46	2.85 ± 1.20	

**Table 9.** Means ± SD for main effects for medial-lateral maximum sway amplitude



	One Leg Stance Task	Balance Leg Reach Task	Group Mean
Control Group	0.32 ± 0.05	0.64 ± 0.28	0.48 ± 0.26
Genu Recurvatum Group	0.32 ± 0.03	0.84 ± 0.49	0.58 ± 0.43
Task Means	0.32 ± 0.04	0.74 ± 0.40	

**Table 10.** Means ± SD for main effects for medial-lateral mean sway amplitude.

	One Leg Stance Task	Balance Leg Reach Task	Group Mean
Control Group	1.69 ± 0.25	3.04 ± 0.41	2.37 ± 0.76
Genu Recurvatum Group	1.65 ± 0.36	3.54 ± 0.94	2.60 ± 1.19
Task Means	1.67 ± 0.31	3.29 ± 0.75	

**Table 11.** Means ± SD for main effects for medial-lateral mean sway speed.

	BLRT Control	BLRT Recurvatum	BLRT Pooled
APMax	0.70*	0.56	0.62*
APMean	0.20	0.56	0.43*
APSpd	0.22	0.003	-0.01
MLMax	0.58	-0.13	0.04
MLMean	0.52	-0.07	0.05
MLSpd	0.49	0.05	0.06
BLRT	1.00	1.00	1.00

\*p<0.05

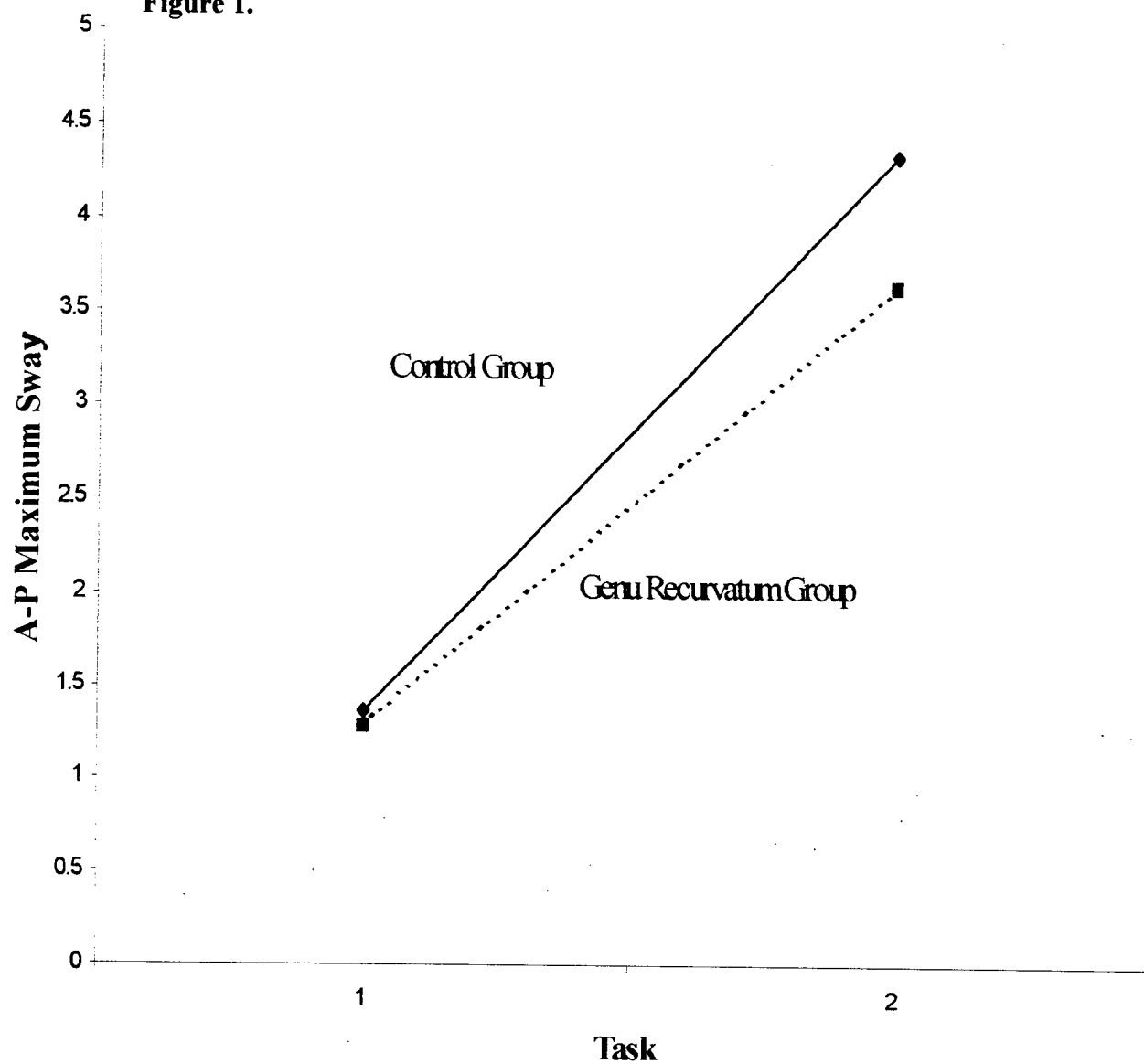
**Table 12.** Pearson correlation table for relationships between BLRT (Balance leg reach test) and force plate variables, for control group, genu recurvatum group, and pooled data for both control group and genu recurvatum group. APMax= anterior posterior maximum sway amplitude; APMean= anterior posterior mean sway amplitude; APSpd= anterior posterior mean sway speed; MLMax= medial lateral maximum sway amplitude; MLMean= medial lateral mean sway amplitude; MLSpd= medial lateral mean sway speed.

## FIGURE LEGEND

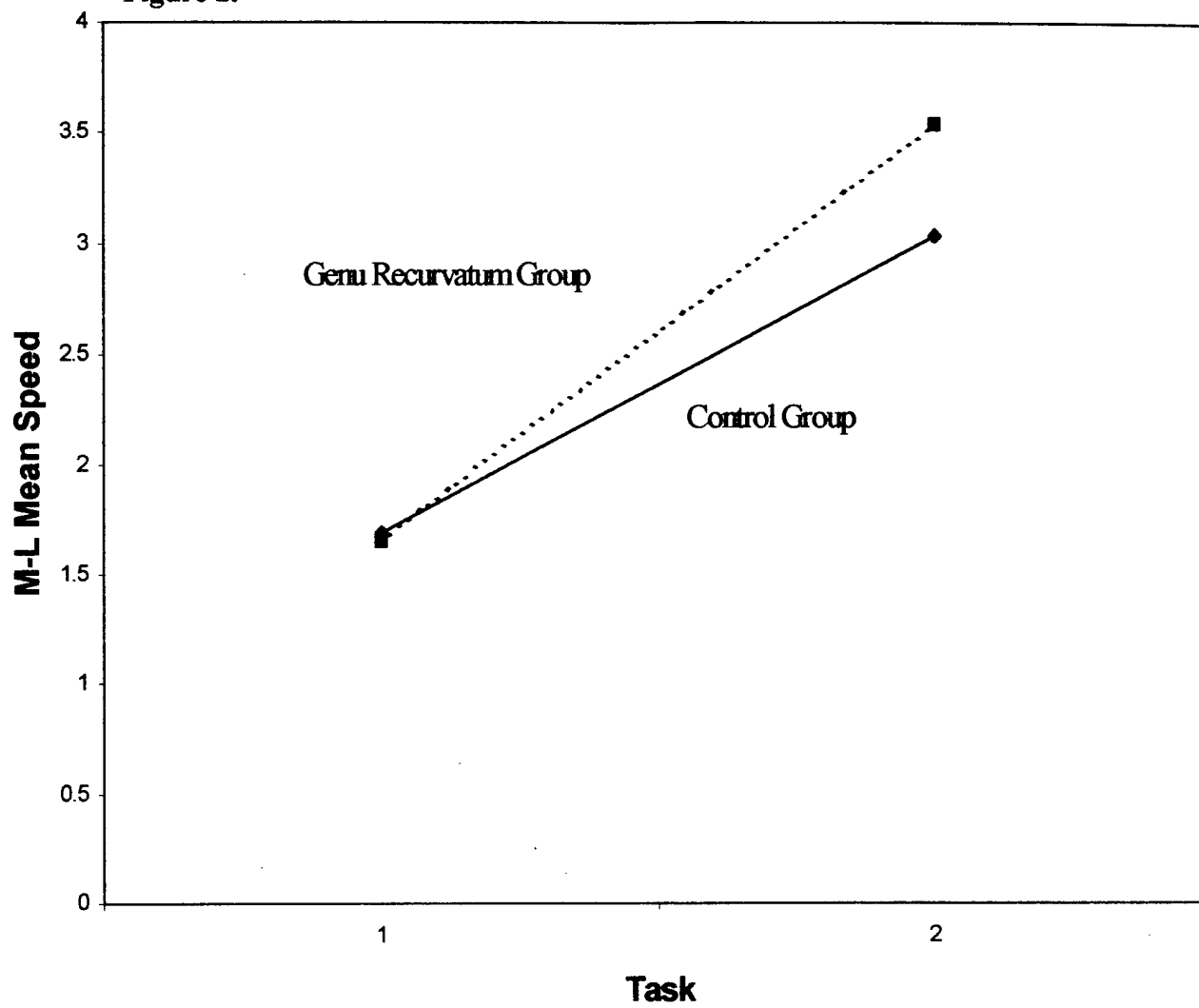
Figure 1. Graph of interactions between group and task for anterior-posterior maximum sway amplitude, for control and genu recurvatum groups.

Figure 2. Graph of interactions between group and task for medial-lateral mean sway speed, for control and genu recurvatum groups.

Figure 1.



**Figure 2.**



## I. APPENDIX 1: FORMS AND INSTRUCTIONS

### A. SUBJECT QUESTIONNAIRE FOR BALANCE STUDY

Date:

Name: Subj. ID \_\_\_\_\_

Age: HT:

Gender M F WT:

1. Do you currently have knee pain? No Yes If yes: Right Left Both
2. Do you have a history of knee pain related to activity? No Yes If yes, what activity?  
\_\_\_\_\_ How long ago? \_\_\_\_\_ (mo) How long did it last? \_\_\_\_\_ (mo)
3. Do you have any history of knee injury? No Yes If yes, how long ago? \_\_\_\_\_ (mo)
4. Do you have a history of knee ligament or ankle surgery? No Yes
5. Have you sprained either ankle or knee, or injured your hips or back within the past 6 weeks? No Yes
6. Have you had any injury within the past month that caused you to alter your normal activities for more than 2 days? No Yes If yes so what happened:  
\_\_\_\_\_
7. Do you wear bifocals? No Yes
8. Do you have any known or diagnosed condition that effects your balance? No Yes  
What? \_\_\_\_\_
9. List any sports or recreation you have actively participated in during the past year.  
Sport, Recreation, or other activity # times/week Ave. time (min)/episode
  - a.
  - b.
9. Select a category from the attached activity rating scale that represents your present activity level. \_\_\_\_\_

B. DATA COLLECTION SHEET (For researcher only)

1. Have you exercised in the previous 2 hours? Y N If yes, can't test today.
2. Have you taken alcohol within the past 24 hours? If yes, can't test today.
3. Are you taking medication that might cause you dizziness? N Y, if yes what? \_\_\_\_\_
4. Foot position High \_\_\_\_\_ Low \_\_\_\_\_ Normal \_\_\_\_\_ Kicking leg: L R
5. Joint mobility assessment R L
 

5 <sup>th</sup> finger	_____	_____	BLR Distance (cm)		
thumb	_____	_____	(Reach leg)	Rt	Lt
elbows	_____	_____	Trial 1	_____	_____
knees	_____	_____	Trial 2	_____	_____
back	_____	_____	Trial 3	_____	_____
5. Measured ankle DF \_\_\_\_\_ R \_\_\_\_\_ L (degree)
6. Measured genu recurvatum: \_\_\_\_\_ R \_\_\_\_\_ L (degree)
7. Weight lifted in <70° squat \_\_\_\_\_ R \_\_\_\_\_ L Acceptable, No Yes
8. Number of OLS Trials R \_\_\_\_\_ L \_\_\_\_\_
9. Number of BLR Trials R \_\_\_\_\_ L \_\_\_\_\_

### C. SPORTS ACTIVITY RATING SCALE

Level I		
4-7 days per week	100	Jumping, hard pivoting, cutting, (basketball, volleyball, football, soccer, gymnastics)
	95	Running, twisting, turning (racquet sports, baseball, hockey, skiing, wrestling)
	90	No running, twisting, jumping (jogging, cycling swimming)
Level II		
1-3 days per week	85	Jumping, hard pivoting, cutting, (basketball, volleyball, football, soccer, gymnastics)
	80	Running, twisting, turning (racquet sports, baseball, hockey, skiing, wrestling)
	75	No running, twisting, jumping (jogging, cycling swimming)
Level III		
1-3 times/ month	65	Jumping, hard pivoting, cutting, (basketball, volleyball, football, soccer, gymnastics)
	60	Running, twisting, turning (racquet sports, baseball, hockey, skiing, wrestling)
	55	No running, twisting, jumping (jogging, cycling swimming)
Level IV		
No sports possible	40	Activities of daily living with no problems
	20	Activities of daily living with moderate problems
	0	Activities of daily living with severe problems

(from Noyes et al, 1989)



#### D. INSTRUCTIONS FOR SUBJECTS

The first task is to balance on one leg.

You are to stand as still as possible, looking straight ahead at the symbol on the wall. I will ask you to stand on your (R/L) foot in the center of the force plate. You will place your hands on your hips, and breathe easily. I will say "ready, set, go"...

On the word "set", raise your non-balance foot onto the toes.

On the word "go", lift that foot just enough to clear your toes.

Try not to touch down, or touch your other leg during the 15 second balance test, but you may do what else you need to maintain balance. When I say "OKAY" you may place both feet down, and step off the plate. You will alternate legs for balance for each of the three trials.

The second task is called Balance Leg Reach.

You will stand with your second toe aligned with the tape at the front edge of the force plate. Your hands will rest on your hips. You will balance on one leg, while maintaining that foot flat on the force plate. You will push the shoebox forward as far as possible using a continuous motion... You will maintain contact with the box. Do not kick or punch the box. Maintain your balance as best you can, trying not to touch down.

I will say "ready, set, go"...

On the word "ready" come onto the toes of the non-balance foot.

On the word "set" lift the non-balance foot up...

On the word "go", begin to push the box.

When completed, return your foot beside the balance foot, and touch down.

So, you will start and stop with your feet beside one another. Again, you will step off the force plate between trials, and alternate legs each time for balance.

## **II. APPENDIX 2: REVIEW OF LITERATURE**

### **A. Introduction**

The following pages summarize a review of some of the literature pertaining to knee joint stability and postural control. Section one begins with a review of the intrinsic and extrinsic factors that contribute to the stability of the tibio-femoral joint. The next section focuses on the contributions of the afferent nervous system to proprioception at the knee joint. The effects of injury on the function of the knee joint are discussed along with the effects of training on reducing those impairments.

Section three begins with a review of hypermobility. Hypermobility is defined and discussed based on a current grading system. A review of the effects of generalized hypermobility leads into a focused discussion of the specific effects of knee joint hypermobility or genu recurvatum. The pathology associated with this condition is described, and relevant studies linking similar conditions are reviewed.

This chapter concludes with a discussion of human balance. Components of balance are reviewed, with a focus on the somatosensory system. Methods of measuring balance are compared, and the use of force plate technology is described. The effects of various physical factors on measures of postural control are discussed. The review concludes with a summary of the above topics, and establishes the rationale for testing subjects with knee hyperextension for possible balance deficits.

### **B. Tibio-femoral Joint Stability**

The stability of the tibio-femoral joint (TFJ) is an important part of normal knee function, and is a critical part of performance for many athletic endeavors. Contributions to TFJ stability derive from both extrinsic and intrinsic factors.

#### **1. Intrinsic Factors**

Among the intrinsic factors are the osseous architecture, joint compressive forces, and passive restraints (49). The osseous elements of stability include the convex surfaces of the femoral condyles which articulate with the concave surfaces of the tibial plateau. In

addition, the surface of the tibia where most of the contact takes place has a slope downward  $9^{\circ}$  posteriorly (86), which helps keep the femur in place during standing. The patella helps to restrain the anterior sliding of the femur on the tibia. (86). The two fibrocartilaginous menisci are thicker peripherally, and serve to deepen the contours of the joint surface, thus providing more contact area for the femoral condyles (123).

Shoemaker and Markolf (106) reported that joint load was effective in limiting anterior laxity in an anterior cruciate deficient specimen at low speeds. Another component of the osseous architecture that enhances stability is the "screw home mechanism", which is a result of the longer medial femoral condyle and the guiding restraint of the cruciate ligaments. Finally, the eminence of the tibial spine rising into the intercondylar notch affords a measure of stability to shearing forces. Further passive support is provided by the joint capsule and the ligamentous structures.

The capsule of the knee joint is the most extensive in the body (121). The attachments of the capsule to the bone follow the articular surfaces of the patella and tibiofemoral joint. Kapandji (69) describes the capsule as a cylinder with a posterior invagination, due to the fact that it courses into the intercondylar region posteriorly. The capsule is reinforced medially by the tibial collateral ligament, and posteromedially by the posterior oblique ligament (62). Posterolaterally the capsule receives static and dynamic support from the arcuate complex (121). Together these combined structures have a common goal of preventing excessive rotary motion of the tibia. In addition, the joint capsule is richly innervated with mechanoreceptors, thus having an additional role in the stability of the joint which will be discussed in a following section.

Ligaments help guide normal movement, and are the primary restraints to non-physiologic joint motion. Ligaments are composed of non-contractile collagenous tissue and attach from bone to bone. In several areas they send fibers to the menisci, or blend with the capsule as noted previously. As static stabilizers ligaments can be grouped into medial and lateral compartments. The deeper or capsular component both medially and laterally is attached to the menisci. The middle third of each ligament is strong and is supported by the tibial collateral ligament (TCL) medially and the iliotibial band laterally

(62). The TCL is the primary restraint to valgus rotation, providing 78% of the restraining force at 25 degrees of knee flexion (93).

The anterior cruciate (ACL) arises from the medial aspect of the lateral femoral condyle and courses anteromedially to the tibial eminence. Its fibers align parallel to the tibia when the knee is flexed 90 degrees (62). The ACL is the primary restraint to anterior translation of the tibia on the femur, providing 85% of the restraint force to an anterior drawer force at 30 degrees of knee flexion (93). Hawkins et al (57) reported that 86% of non-operated ACL tears had subsequent problems with giving away. In contrast to its role as a primary static stabilizer, one research group has reported that ACL loads were less than 10% of loads presumed in the dog tendon during certain functional activities (77). This conclusion might suggest the importance of a neurosensory role for ligaments in common activity. The afferent role of ligaments will be discussed further in the next section.

The posterior cruciate ligament (PCL) crosses behind the ACL from the medial aspect of the medial femoral condyle to the lateral aspect of the tibia. It is the primary restraint to posterior translation of the tibia on the femur. The PCL provides 95% of the restraint to posterior drawer in clinical laxity testing (93). The fibular collateral ligament (FCL) is the primary restraint to varus rotation. The FCL provided 68% of the restraint to lateral opening at 25 degrees of knee flexion (93). The ACL and PCL together restrict knee hyperextension (62). The PCL remains taught throughout the range of motion. This ligament appears to be in the center of the joint, and is the axis about which flexion, extension, and longitudinal rotation motions occur (62).

## 2. Extrinsic Factors

Extrinsic contributions to the support of the knee joint are derived primarily from the active support of the muscles and the related aponeuroses which provide dynamic stability. This support is governed by both voluntary and reflex muscular contractions. Evidence is inconclusive regarding the magnitude of the role of muscle in the ligament deficient knee, however. Solomonow et al (112) concluded that hamstring muscles were reflexively activated from mechanoreceptors in the ACL, the muscle, and the capsule.

Furthermore, this reflex arc may serve as an “on-demand” torque regulator to help maintain joint stability. Gauffin and Tropp (40) have reported that subjects with old ACL ruptures demonstrate altered movement and muscle activation patterns on the injured leg, which may allow them equivalent jump length on a functional test. Pope et al (99) demonstrated that contraction of the vastus medialis and sartorius increased the valgus stiffness of the knee, however, they concluded that the contraction occurred too late to protect the knee in a simulated ski injury condition. Huston and Wojtys (64) found that female athletes and controls demonstrated less muscle strength and endurance, and more anterior tibial laxity than male counterparts. Other studies of subjects with knee joint OA suggest functional improvement following quadriceps strengthening rehabilitation (33,85,109), which although not specifically stated, might be construed to include improved joint stability or control.

Clinical testing of knee joint stability is performed either manually by a series of specific ligament stress tests, or by instrumented testing. One problem with assessment of joint stability in this fashion is that clinical measures of stability do not always reflect functional outcomes. Several investigators have examined this issue (6,10,56,95,111,115). Snyder-Mackler et al (111) found measures of anterior laxity in ACL deficient subjects did not relate to functional outcome. Harter et al (56) found both instrumented measurements of joint laxity as well as clinical orthopedic tests correlated poorly with patient perceived outcomes.

In summary, the stability of the knee joint is derived from the complex interactions of multiple factors. Pathology or injury to bony, ligamentous, capsular or muscular tissues of the knee can result in instability or abnormal function of the joint. The relationship between stability and function is not clear however. A discussion of the specific effects of alteration or injury of the neurological component follows.

### **C. Peripheral Neural Mechanisms in Proprioception**

Afferent neurology of the knee plays a critical role in providing sensory feedback to the central nervous system on the state of the articular and peri-articular tissues of the joint. Adequate function of this system is essential to normal joint stability and control.

Past researchers like Freeman and Wyke (35,126), are among the great contributors to our knowledge of the neural inputs that originate around joints. Sherrington coined the term proprioception to describe the input that originated from joint, muscle, tendon and associated deep tissues (103). Proprioception might be more completely defined as a specialized sense of touch encompassing the sensation of joint movement (kinesthesia) and joint position (joint position sense) (75). These sensations are mediated by specialized nerve endings called mechanoreceptors located in the peri-articular soft tissues, including skin, muscle, ligaments and joint capsule.

The knee is innervated by the posterior articular and obturator nerves, and the articular branches of the femoral, common peroneal and saphenous nerves (71). These constituent nerves appear to have a spatial territory, and send branches to other tissues such as the ligaments and capsule (71). Embedded in the periarticular connective tissue are the joint mechanoreceptors. These highly specialized receptors are subject to distortion by stretch, relaxation, compression, and fluid tension changes (103). The quantity and speed of electrical discharge that ensues from the receptor is a function of spatial and temporal factors as well as the specificity of the receptor and the size of the nerve fiber associated with it.

Laboratory studies by Freeman and Wyke (35), and Burgess and Clark (23), revealed the primary morphological and functional characteristics of these nerve endings. There remains a lack of agreement in the literature as to the specific location and role of the mechanoreceptors. Most noteworthy, is the low threshold, slowly adapting receptor called a Ruffini ending, which responds with variable impulses to movement in either flexion or extension, and which exhibits a constant baseline discharge when a level of stimulation is maintained (9). Conversely, the low threshold, rapidly adapting receptor called a Pacinian corpuscle, exhibits a rapid burst of impulses in response to change in joint direction or speed, followed by a rapid decline of discharge (9). Wyke (126) associates postural and kinesthetic awareness to the slowly adapting mechanoreceptors. Grigg (49) states that the Ruffini-type mechanoreceptors are stretch sensitive, are excited by capsule stresses, and function as limit detectors. Grigg (49) also states that the

Pacinian-type mechanoreceptor is compression sensitive, so that when stimulated it mediates a sense of compression.

Debate exists regarding the existence of mechanoreceptors in ligaments. Kennedy (71) reported that no specialized receptors were recognized in the human ACL. In contrast, numerous animal studies have demonstrated neural tissue, including recent cat studies by Krauspe (74), and Gomez-Barrena (46). Although Krauspe et al (74) report that mechanoreceptors in the ACL are markedly activated when the joint is hyperextended and rotated, Grigg (49) states that the contribution to joint proprioception is minor due to the paucity of nerves, and their lack of specificity as limit sensors.

Simple mapping and density typology do not appear to dictate functional relations between afferent receptors and joint dynamics. Studies on the dorsal root filaments of posterior articular nerve fibers in the cat, showed that of 207 fibers, 140 responded in both marked flexion and marked extension of the knee, while only 47 fibers responded solely to flexion and 12 solely to extension (23). Outward twisting of the tibia enhanced the output of most slow adapting fibers (23).

The exact nature of the interactions of articular receptors is more complex and diverse than previously reported. Rowinski (103) concluded that functionally, the processed neural information: 1) protects the joint from movement beyond its normal range; 2) helps to determine the muscle activity necessary for smooth movement; and 3) participates with the other afferent receptors to provide the CNS with an image of the limb position relative to the body. Based on these criteria, a normally functioning afferent system could be investigated by tests of muscle function, as well as joint movement and position sense.

### 1. Effects of Injury

The affects of joint injury or pathology on the function of the afferent system have been extensively investigated by examining proprioception (8,11,38,51,75,108); muscle function (28,40,71,79); functional activities (83,95,111,115,116); and balance (26,37,45,117). Barrett (10) noted altered proprioception following ACL damage by measurement of joint position sense, whereas Barrack (8), measuring threshold to

detection of movement in controls and ACL deficient knees, reached a similar conclusion. Barrett et al (10) also concluded that proprioception correlated highly ( $r = 0.84$ ) with function following ACL reconstruction. Conversely, Harter et al (56) studied the relationship between multiple predictor variables and ACL reconstructed patient perceived outcomes, concluding that joint laxity measurement and joint position sense did not correlate with patients perceived outcomes. Barrack (8), finding no difference in threshold to detection of motion between acute and chronic ACL deficient subjects, concluded that perhaps proprioception loss was a cause not a result of ACL deficiency. Friden et al (38) reported that ACL deficient knees had impaired awareness in detecting movement mainly in the nearly extended position,  $20^\circ$ , which is a joint position similar to many weight bearing activities. Wyke (126) has reported that an injury to cat joint ligaments or capsule, influences muscle activity not only adjacent to the joint, but also remotely associated muscle activity. Reflex quadriceps inhibition has been demonstrated following induction of fluid into the joint (28,71). Patients with early osteoarthritic have been described as having arthrogenic motor inhibition related to sensitized joint receptors (63). Lofvenberg et al (79), similarly, reported prolonged muscle reaction times with chronic ankle instability. Numerous investigators have examined postural sway following ankle sprain (26,37,88,122), but comparatively few studies have examined the effect of knee injury, or pathology on postural sway (39,55,88,122). Both Mizuta et al (88) and Friden et al (39) have reported on increased postural sway in ACL deficient knees.

## 2. Effects of Training

Rehabilitation training is frequently prescribed for individuals with altered joint proprioception, or functional deficits. Training may include static or dynamic activity. Additional information will be reviewed in the section on balance. The positive effect of training on the function of the proprioception system has been demonstrated by several authors (5,65,127). Barrack and Skinner (7) reported on the "paradox of training" among professional ballet dancers. Specifically the authors reported that dancers were less accurate in reproducing knee angles, but had a lower threshold to detect joint position change, which they attributed to the dancers' level of professional training (7).



In summary, a primary role of the afferent system of the joint is that of proprioception. The complexity of this role might well be summed by Rowinski's (103) conclusion that neuron population response patterns are the encoder of joint stresses and strains. He states that the neuron population must reflect the 1) static joint angle; 2) velocity of joint excursion; 3) planes of joint movement; 4) active or passive motion; 5) and the nature of internal or external compressive forces on the articular soft tissue (p.58). While the effects of trauma are not inconclusive, ample evidence suggests that altered proprioception or balance can result from injury.

#### **D. Joint Hypermobility**

Joint mobility, like joint stability, is influenced by both intrinsic and extrinsic factors. Intrinsic factors include osseous structure; presence and structure of fibrocartilage; capsular and ligamentous tissue length and elasticity; muscle and tendon length and tone; and skin elasticity. Elasticity of tissue is a function of the degree of hydration, and the composition of fibrous connective tissues collagen and elastin. Collagen cross links increase with age, which tends to make tissues more rigid (87). More elastic tissues have higher percentages of elastin. Extrinsic factors including gravity, ground reaction forces, posture, inertia, exercise (109,113), and temperature also influence joint mobility.

##### **1. Grading Joint Mobility**

Hypermobility can be defined as excessive joint range of motion, or the extreme of widely variable joint mobility (72). If this condition is non-pathologic, it may also be called joint laxity. In contrast, clinical or mechanical instability refers to excessive gross movement or pathological hypermobility (36,84). Describing levels of joint mobility can be difficult. One frequently used system grades joint mobility from 0-6, with 0 being ankylosed, 3 = normal, and 6 = unstable (68). A general rule for assessing mobility is to compare one limb to the contralateral limb, or to use the concept of tissue end-feel to assess the nature of the end point of motion (27). Carter and Wilkinson (24) were perhaps the first to devise a method of classification for generalized laxity. Their method entails

the examination of both upper and lower limbs, fingers, thumbs, elbows, knees and ankles for the presence of excessive motion (24). They reported that generalized joint laxity was present when >3 pairs of joints were rated positive. This method was later modified and refined by Beighton and Horan (13), who replaced the ankle component with a trunk component for which the subject bends over to touch the floor (13). Hypermobility was subsequently associated with a score equal to or greater than 3 on the 0-9 point scale. A reliability study recently reported intra-rater and inter rater perfect agreement on composite mobility scores among college age females, at 69% and 51% respectively, and 81% and 89% for agreement on mobility category scores (21). The arbitrary cutoff point of 10° for elbow and knee hyperextension was cited by the author as one weakness in the scoring index.

## 2. Prevalence and Etiology

Generalized joint laxity has been described and investigated by numerous authors. (13,15,24,47,60). Kirk, Ansell, and Bywaters (72), described the hypermobility syndrome in 1967. These authors characterized the syndrome as featuring increased musculoskeletal complaints and joints that were unduly lax in otherwise healthy normal subjects (72). At least two types of hypermobility have been described, one type is transient and related to maternal hormonal effects on the baby, and the second type is persistent and seems to have a familial linkage.

Hypermobility was demonstrated in 7% of a normal school age population or 6-11 year old boys and girls (24). This percentage was substantiated in a subsequent study (13). Other investigators report a higher incidence of hypermobility among females (13). General agreement exists that mobility decreases with age (13,15,24). The associated effects of hypermobility have been the topic of numerous papers.

## 3. Effects of Hypermobility

Among girls with congenital hip dislocation, just under one-third showed generalized joint laxity, compared to 75% of the boys in this study (24). Recurrent knee joint pain and effusion was noted in 13 military trainees with joint laxity (114).

Hypermobility has also been associated with osteoarthrosis (16). Osteoarthritis related to hypermobility is reported to occur in the knees, back, hands, and spine (105). Untreated generalized ligament involvement may cause children to fatigue easily, have night pains, and have increased fat deposits due to decreased activity or clumsiness (61). Poor posture, knock-knees, hyperextended knees, and weak arches were all considered indicators of hypermobility, and were reported by the same investigator (61). Another clinical report on 114 patients at a rheumatology clinic, listed both articular and extra-articular features of the hypermobile group (31). Associated conditions included entrapment neuropathies, varicose veins, and piles (31). In contrast, Lewkonja (78) argued that even in persistent hypermobility through the 7<sup>th</sup> decade, it is rare for general hypermobility to cause general osteoarthritis. Bird et al (16) reported on a study involving self assessed joint mobility, and the radiographic evidence of osteoarthritis in physical education teachers. The authors concluded that although a few trends were present in their data, no statistical evidence between osteoarthritis and either inherited or acquired joint laxity existed (16).

In addition to these multiple negative physical complaints, other effects of hypermobility include the reported benefits in certain athletic endeavors such as gymnastics, swimming, and ballet. Good flexibility is generally considered to increase an athlete's chances of avoiding strain or tears of connective tissues (3). While some authors report an increased incidence of joint hypermobility favoring selection in ballet dancers (47), others report that only those joints that are trained show such mobility (73).

Several authors have investigated the possible association between joint laxity and predisposition to injury. These studies included athletes in professional football (92); college football (67,89,125); high school football (42); gymnastics (22,125); basketball (125); and non-specific athletics (81). Results from these studies are mixed. Some investigators claim positive associations between mobility measures and ligament rupture (39,92) or injury (81,125), others report no significant association (22,42,67,89). Harner et al (54) conducted a retrospective study of bilateral ACL injured athletes, including clinical tests, hypermobility tests, and computerized tomography. Their conclusions suggested anatomic factors related to the width of the lateral femoral condyle, and a

possible congenital aspect that might account for the differences between injured and non-injured subjects (54). The hypermobility testing did not include the knee because of the presence of injury, nor was the possible connection between familial history of ACL injury and joint laxity given much discussion.

Lack of agreement exists as to what is considered normal range of motion of the knee. The range for flexion has been given as  $130^{\circ}$  (59), and up to  $160^{\circ}$  (69). The range of reported extension also varies by author from at least  $0^{\circ}$  to a few degrees beyond (59), and up to  $5-10^{\circ}$  of hyperextension (69). It appears that there is considerable evidence to suggest that hypermobility may cause musculoskeletal problems. The specific effects at the knee will be examined in the next section.

### **E. Genu Recurvatum**

A common feature of hypermobility is genu recurvatum, or knee hyperextension. The incidence of hyperextension is not clear because of the paucity of investigations into this area. Arangio et al (2), however, reported that 46 (9.8%) of their sample of high school athletes had asymptomatic unilateral hyperextension. This agrees in part with the prevalence of hypermobility of 7% as reported by Carter and Wilkinson (24).

The exact cause of hyperextension is not always clear. Knee hyperextension has been associated with ligamentous or capsular laxity (13,24,61), muscular weakness of the posterior knee, weakness of the gastrocnemius (70), tightness of the gastrocnemius or achilles tendon (98), quadriceps contracture, or as a consequence of neurological damage or compensation for lower extremity asymmetry (98). Genu recurvatum is often observed during standing postural assessments. The degree of hyperextension can be measured in stance or supine, and ranges from  $5-15^{\circ}$  beyond the zero degree point (59,69).

Whether hyperextension is a benign entity or not is not clear. Standing quietly with the knees locked into hyperextension can be a compensation for weak quadriceps (95). Whether this results in over-stretching the posterior restraints of the joint or not is unclear. Perry (98) has discussed the potential damage or pain that may result from hyperextension during gait. Radin (102) has described the "quadriceps avoidance gait," in which subjects maintain the knee near full extension at heel strike. The increase in

ground reaction forces from impulsive loading through a hyperextension joint has consequences related to mechanical wear on articular cartilage. Axe et al (4) have reported on the increased articular damage in chronic ACL deficient knees who also had >3cm hyperextension. A recent investigation also reported that hyperextension is a significant predictor of group for ACL injured college age females (81).

The affect of hyperextension on knee joint proprioception has been investigated, but is still controversial. Ballet dancers with knee joint laxity were tested for joint proprioception and kinesthesia by Barrack and Skinner (7), who describe a "paradox" of decreased accuracy of joint position sense, but lower response threshold to perceptible movement in the trained dancers. In contrast, Hall et al (53) reported significantly higher thresholds to perception of movement in ballet students with knee hyperextension than controls. Both of these studies utilized the classic non-weight bearing approach to measure joint proprioception (7,53).

The question of whether proprioception is the same in weight bearing as in non-weight bearing has recently been addressed (1,58). In both studies, healthy subjects were asked to replicate knee flexion angles in non-weight bearing and weight bearing. Although the procedure differed slightly in the two studies, both authors concluded that angle replication was better in weight bearing. Higgins and Perrin (58) also examined anterior knee joint excursion for a relationship to joint angle replication, but found a weak correlation in both weight bearing ( $r=0.04$ ), and non-weight bearing ( $r=0.17$ ). Barrak et al (9) have argued, however, that joint angle replication is less sensitive a measure than threshold to detection of perceptible movement.

Whether hyperextension at the knee has an affect on joint proprioception is not clear. Likewise, whether balance or neuromuscular control is altered in individuals with hyperextension is not known. Evidence exists to suggest an association between balance, proprioception, strength and joint laxity. Further research regarding the nature of these relationships could provide helpful data needed to clarify these relationships.

## **F. Knee Joint in Postural Control and Function**

The terms postural control, balance, and maintenance of upright stance are used interchangeably when reviewing the literature on human movement. The topic of human balance or postural control has been the focus of considerable research and inquiry. Although several definitions for balance are available, it appears that there is general agreement that there are at least two modes: one being static balance, or steadiness; the second is dynamic balance which implies either intentional or reactive movement. Horak (60) has reported, several functional components exist for postural control, including the biomechanical, the motor coordination, and the sensory organization component. Any study of postural control must acknowledge an appreciation of the complex interactions of the three systems involved: visual; vestibular; and somatosensory. The interest for this paper is the somatosensory system, in particular that portion associated with the knee, which contributes to the stability of the joint.

The term stability is a characteristic of balance that can be operationally defined (104). Stability can be expressed as either a static or dynamic state. The kinematic outcome of maintaining stability may be defined as postural control (104). As discussed in sections one and two, stability at the knee is a function of the combined action of the ligaments, muscles, and nerves of the joint. These elements of the somatosensory system are in keeping with the functional components described by Horak (60).

### **1. Measurement of Postural Control**

Clinical measures of postural control are most commonly used to assess patients with neurological problems, or problems related to falls in the elderly. Methods of assessing postural control include: timed standing balance tests (18); ordinal scales of steadiness (17,55); functional reach tests (14); and force plate tests (30,41,43,82,118), which attempt to quantify postural steadiness. While each of these methods has value, the force plate may be considered the most sensitive tool.

Force plate output can be used to determine ground reaction forces and moments of force, as well as center of pressure, which is equal and opposite to all the downward acting forces from the body (124). During relatively stable stance, the center of pressure

is a reflection of the vertical projection of the center of gravity of the body. Information derived from center of pressure measures can be used to quantify balance or lower extremity neuromuscular function. Winter (124) states that the center of pressure is really the neuromuscular response to imbalances of the center of gravity of the body. The use of the force plate to assess joint stability has been described extensively in studies of reported functional instability associated with ankle ligament injury and laxity (26,37,45,117,118), and to a lesser degree in studies of knee stability (39,55,88,127). Although simpler clinical tests of postural control do exist, the objectivity and sensitivity of these tests is somewhat controversial, and the results do not generalize well to a healthy younger population (14,18). Force plate tests of functional instability use measures of steadiness such as center of pressure variability, to assess the effects of an injury on an athlete's postural control. These tests usually compare the injured and uninjured extremity (14,29,30), or compare injured to uninjured athletes. The relationship between most functional tests of lower extremity control and postural control, however, is not clear.

Friden (39) reported that the standard deviation of the center of pressure variation, the number of oscillations exceeding 5 mm and 10 mm, and the average speed of oscillations were significantly greater in 19 subjects with ACL insufficiency than a control group. Mizuta (88) used force plate measures of sway area and length of sway path to demonstrate greater unsteadiness in a group of ACL deficient subjects who had functional instability associated with cutting sports. Conversely, Harrison et al (55) were unable to demonstrate a difference in a dispersion index between the healthy leg and the ACL reconstructed leg in subjects 10-18 months post surgery. This subject group, however, did have balance training as part of their rehabilitation program. Of interest is the report that only 47% of the ACL injured group were able to complete a ten second eyes closed one leg stance test, in comparison to 62% of the control group. Whether this difference was statistically significant was not reported. Further insight into the use of force plate measures as a valid and objective assessment of knee joint stability could prove valuable, for example, regarding an athlete's safe return to sport. Several investigators have reported on the degree of variability of center of pressure measures under conditions of quiet standing (30,41,90,97). The magnitude of intra-subject variability was examined by

Geurts et al (41) using of the coefficient of variation (defined as standard deviation of the parameter divided by the mean x 100). These investigators reported values for anterior-posterior and medial-lateral peak to peak amplitude 28% and 34%. Applying this formula for the mean anterior-posterior sway values given for the Ekdahl study (30) yielded coefficients of variation of 25%, and the value for medial-lateral sway was 33%. The results of repeated testing indicated that the velocity center of pressure measurement (CV=22%), was the most consistent variable in the anterior-posterior direction, and that the force center of pressure (CV=29%) was the more consistent in the medial-lateral direction. These values reflect the fact that the variability of normal postural sway as measured by the force plate is considerable within subjects. Several studies on normal subjects of different ages have documented the degree of inter-subject variability (30,100). Murray et al (90) concluded that the center of pressure constantly fluctuated randomly and without rhythm during single leg standing. Patla et al (97), however, stated that despite large fluctuations the center of pressure and mean power frequency remain relatively constant.

Various physical factors also are reported to have an effect on force plate measures of postural control, including: leg dominance (30,34), leg strength (30), ankle injury (26,37,45,115), knee injury (55,88,127), age (17,32,52,90,100), vision (30,43,100), gender (30,34), height (34), and task difficulty (32,43,90). Conversely, other investigators reported no effect on force plate measures of postural control associated with: leg dominance (26,39,43,55), gender (52), height (30), weight (30), and leisure activity (30). Balance training has been shown to have a positive effect on postural control (5,18,80,117,127).

## 2. Functional Testing

The value of a clinical test rests in part upon whether it is valid, reliable, and sensitive. In a portion of a translated report (120) written by M.H. Romberg on 1851, a procedure used for assessing equilibrium reveals the simplicity of this early balance test. Romberg stated that only those with an equilibrium problem fail this test. Therefore, one would consider this test valid and reliable for equilibrium problems. Several investigators



have since tried to quantify this test and make it more objective (17,55). One functional balance test, the Berg Balance Measure (14), has been shown to be highly reliable (intraclass correlation coefficient =0.98), but such a test may not be appropriate for healthy athletic populations.

Functional knee joint stability testing for athletes typically involves dynamic weight bearing activities. Functional testing is commonly used to determine an athlete's ability to return safely to sport or activity following a ligament injury. Although reliability has been investigated for several of the tests (20), the predictive validity of many of these tests is not without question (6,89,95,115,116). Barber et al (6) reported that 50% of ACL deficient patients performed normally on the one legged hop test, although all reported functional instability with sports. Subsequent analysis of functional tests revealed that the sensitivity to confirm lower extremity abnormality improved to 62% when using two tests (95). One functional test is the balance-leg-reach test. In this test, subjects balance on the affected leg while the distance they extend the other foot forward is measured.

Greenberger et al (48) examined this test along with two additional lower extremity tests, to determine rationale and reliability to assess lower extremity function, and reported the intra-class correlation coefficient for test-retest reliability for the balance leg reach was between 0.73 and 0.91. Qualter et al (101) reported that values for the balance leg reach test were significantly greater for controls than ACL deficient subjects. Thus, the test might be considered valid and reliable in assessing functional instability (101). Normative values for this test have not been reported.

Because knee joint hyperextension is not always associated with a prior ligament injury, individuals with this condition may not be as carefully screened during pre-participation testing as someone with an existing ACL injury. A sensitive, objective, and reliable test of balance could be useful in settings with significant populations of active younger clients. Several studies have been conducted to determine if force plate measures are sensitive and reliable. One aspect of force plate measurement that has been discussed in the literature, is the selection of appropriate parameters for the given problem or group being investigated. Goldie et al (43) have suggested that force measures are more sensitive than center of pressure measures in evaluating postural control. These

investigators utilized standard deviations to compare the types of measures, and then used correlation statistics to determine which specific parameters were related. Geurts et al (41) have argued that these findings are less significant, because the study did not utilize any frequency dependent measures. Other investigators report that highly correlated measures may be redundant, measuring the same attribute of balance (100). A well conceived study by Prieto et al (100), compared young and older adults under eyes open and eyes closed conditions of bilateral stance, using a multitude of common and "hybrid" force plate parameters. The authors concluded that multiple types of measures are necessary to characterize differences between groups (100).

In summarizing these findings, it is important to understand the variety of testing and data collection procedures available and to select those variables that will be most effective in describing the condition being studied. In order to compare results between studies it is important to choose commonly used variables and definitions. Further inquiry is needed regarding the complex interactions of balance and function based on past and present research efforts. Although some test methods have been improved upon, and others ruled less sensitive or reliable, the search for a "gold standard" or combination of factors that work best for different populations should continue.

### **G. Summary**

With increasing numbers of young people pursuing an active lifestyle, there are increasing numbers of knee joint injuries. Knowledge of the factors that contribute to these injuries is critical to effective injury prevention. In addition, the long term effects of knee injury are not clear due in part to lack of prospective studies.

Evidence suggests that an association exists between knee injury, proprioception and joint laxity. The exact nature of these relationships is not clear. Studies suggest that joint laxity may contribute to altered proprioception, and that this, in turn, may affect postural control. If subtle postural control is an unidentified factor contributing to the incidence of knee injuries, further study in this area may be worthwhile.

While functional testing may have promise in identifying individuals who have ACL deficient knee, many who have injured their ACL have learned to compensate for

this instability by altered movement patterns (40). Altered movement patterns often lead to clinically evident musculoskeletal problems. Whether individuals with hyperextension have altered movement patterns is not clear. Likewise, the sensitivity of functional testing to detect subtle differences in joint control that may be critical under more dynamic loading is not clear, especially for uninjured individuals.

The use of force plate technology shows promise as a sensitive and reliable method of studying postural control and stability under various conditions (30,45,82,119). Further study is warranted in various populations, both to validate the usefulness of the instrument, and to establish a normative database.

## BIBLIOGRAPHY

1. Anderson S, Terwilliger D, Denegar C: Comparison of open versus closed chain test positions for measuring joint position sense. *J Sports Rehab* 4:165-171, 1995
2. Arangio GA, St. Amour-Meyers M, Reed J: Incidence of asymptomatic nontraumatic unilateral knee hyperextension in the high school athlete. *J Sports Rehab* 5:287-292, 1966
3. Arnheim DD, Prentice WE: *Principles of Athletic Training* (8<sup>th</sup> Ed), St. Louis: Mosby-Year Book, Inc., 1993
4. Axe MJ, Lindsay K, Snyder-Mackler L: The relationship between knee hyperextension and articular pathology in the ACL deficient knee. *J Sports Rehab* 5:120-126, 1996
5. Balogun JA, Adesinasi CO, Marzouk DK: The effects of a wobble board exercise training program on static balance performance and strength of lower extremity muscles. *Physiother Canada* 44(4):23-30, 1992
6. Barber SD, Noyes FR, Mangine RE: Quantitative assessment of functional limitations in normal and anterior cruciate ligament-deficient knees. *Clin Ortho Rel Res* 255:204-214, 1990
7. Barrack RL, Skinner HB, Cook SD: Proprioception of the knee joint. (Paradoxical effect of training). *Am J Phys Med* 63(4):174-181, 1984
8. Barrack RL, Skinner HB, Buckley SL: Proprioception in the ACL deficient knee. *Am J Sports Med* 17(1):1-6, 1989
9. Barrack RL, Lund PJ, Skinner HB: Knee joint proprioception revisited. *J Sports Rehab* 3:18-42, 1994
9. Barrett DS: Proprioception and function after ACL reconstruction. *J Bone Joint Surg* 73B(5):833-837, 1991
11. Barrett DS, Cobb AG, Bentley G: Joint proprioception in normal, osteoarthritic, and replaced knees. *J Bone Joint Surg* 73B(1):53-56, 1991
12. Beighton P, Horan R: Orthopedic aspects of Ehlers-Danlos syndrome. *J Bone Joint Surg* 51B(3):444-451, 1969
13. Beighton P, Solomon L, Soskolne CL: Articular mobility in an African population. *Ann Rheum Dis* 32:413-418, 1973

14. Berg KO, Maki BE, Williams JI, Holliday PJ, Wood-Dauphinee SL: Clinical and laboratory measures of postural balance in an elderly population. *Arch Phys Med Rehab* 73:1073-1080, 1992
15. Bird HA, Brodie DA, Wright V: Quantification of joint laxity. *Rheum and Rehab* 18:161-166, 1979
16. Bird HA, Hudson A, Eastmond CJ, Wright V: Joint laxity and osteoarthritis: a radiological survey of female physical education specialists. *Brit J Sports Med* 14(4):179-188, 1980
17. Bohannon RW, Larkin PA, Cook AC, Gear J, Singer J: Decrease in timed balance test scores with aging. *Phys Ther* 64(7):1067-1070, 1984
18. Bohannon RW, Leary KM: Standing balance and function over the course of acute rehabilitation. *Arch Phys Med Rehab* 76:994-996, 1995
19. Bohannon RW: Reference values for extremity muscle strength obtained by hand-held dynamometry from adults aged 20-79 years. *Arch Phys Med Rehab* 78:26-32, 1997
20. Bolgla LA, Keskula DR: Reliability of lower extremity functional performance tests. *JOSPT* 26:138-149, 1997
21. Boyle KL: The hypermobility syndrome and reliability of the Beighton and Horan's joint mobility index. Unpublished master's thesis, University of North Carolina, Chapel Hill, NC, 1997
22. Brannan, TL, Schulthies SS, Myrer JW, Durrant E: A comparison of anterior knee laxity in female intercollegiate gymnasts to a normal population. *J Athl Train* 30(4):298-301, 1995
23. Burgess PR, Clark FJ: Characteristics of knee joint receptors in the cat. *J Physio* 203:317-335, 1969
24. Carter C, Wilkinson J: Persistent joint laxity and congenital dislocation of the hip. *J Bone Joint Surg* 46B(1):40-45, 1964
25. Cohen J: Statistical power analysis for the behavioral sciences, (2<sup>nd</sup> ED), pp 273-311, Hillsdale, NJ: Lawrence Erlbaum Associates, Pub, 1988
26. Cornwall MW, Murrell P: Postural sway following inversion ankle sprain. *J Am Pod Med Assoc* 81(5):243-247, 1991
27. Cyriax J: Textbook of orthopedic medicine, Vol 1 (7<sup>th</sup> ED), London: Bailliere Tindall, 1978

27. Cyriax J: Textbook of orthopedic medicine, Vol 1 (7<sup>th</sup> ED), London: Bailliere Tindall, 1978
28. deAndrade JR, Grant C, Dixon, A: Joint distension and reflex muscle inhibition in the knee. *J Bone Joint Surg* 47A(2):313-322, 1965
29. DeHaven KE, Lintner DM: Athletic injuries: Comparison by age, sport, and gender. *Am J Sports Med* 14(3):218-224, 1986
30. Ekdahl C, Jarnlo G, Andersson SI: Standing balance in healthy subjects: evaluation of a quantitative test battery on a force platform. *Scand J Rehab Med* 21:187-195, 1989
31. El-Shahaly HA, El-Sherif AK: Is the benign joint hypermobility syndrome benign? *Clin Rheum* 10(3):302-307, 1991
32. Era P, Heikkinen E: Postural sway during standing and unexpected disturbance of balance in random samples of men of different ages. *J Gerontol* 40(3):287-296, 1985
33. Fisher NM, Pendergast DR, Gresham GE, Calkins E: Muscle rehabilitation: its effect on muscular and functional performance of patients with knee osteoarthritis. *Arch Phys Med Rehab* 72:367-374, 1991
34. Frandin K, Sonn U, Svantesson U, Grimby G: Functional balance tests in 76-year - olds in relation to performance, activities of daily living and platform tests. *Scand J Rehab Med* 27:231-241, 1995
35. Freeman MAR, Wyke B: The innervation of the knee joint. An anatomical and histological study in the cat. *J Anatomy* 101(3):505-532, 1967
36. Freeman MAR, Wyke B: Articular contributions to limb muscle reflexes: The effects of partial neurectomy of the knee joint on postural reflexes. *Brit J Surg* 53(1):61-69, 1966
37. Friden T, Zatterstrom R, Lindstrand A, Moritz U: A stabilometric technique for evaluation of lower limb instabilities. *Am J Sports Med* 17(1):118-122, 1989
38. Friden T, Roberts D, Zatterstrom R, Lindstrand A, Moritz U: Proprioception in the nearly extended knee: measurement of position and movement in healthy individuals and in symptomatic ACL injured patients. *Knee Surg, Sports Traum, Arthroscopy* 4:217-224, 1996
39. Friden T, Zatterstrom R, Lindstrand A, Moritz U: Disability in anterior cruciate ligament insufficiency, an analysis of 19 patients. *Acta Orthop Scand* 61(2):131-135, 1990

40. Gauffin H, Tropp H: Altered movement and muscular activation patterns during one-legged jump in patients with old ACL ruptures. *Am J Sports Med* 20(2):182-191, 1992
41. Geurts AC, Nienhuis B, Mulder T: Intrasubject variability of selected force-platform parameters in the quantification of postural control. *Arch Phys Med Rehab* 74:1144-1150, 1993
42. Godshall RW: The predictability of athletic injuries: An eight year study. *J Sports Med* 3(1):50-54, 1975
43. Goldie PA, Bach TM, Evans OM: Force platform measures for evaluating postural control: Reliability and validity. *Arch Phys Med Rehab* 70:510-517, 1989
44. Goldie PA, Evans OM, Bach TM: Steadiness in one-legged stance: Development of a reliable force-platform testing procedure. *Arch Phys Med Rehab* 73:348-354, 1992
45. Goldie PA, Evans OM, Bach TM: Postural control following inversion injuries of the ankle. *Arch Phys Med Rehab* 75:969-975, 1994
46. Gomez-Barrena E, Martinez-Moreno E, Munuera L: Segmental sensory innervation of the ACL and the patellar tendon of the cat's knee. *Acta Orthop Scand* 67(6):533-535, 1997
47. Grahame R, Jenkins JM: Joint hypermobility-asset or liability? *Ann Rheum Dis* 31:109-111, 1972
48. Greenberger HB, Sperling L, Frankford G: The rationale and reliability of three functional performance tests in the assessment of lower extremity function. Platform Presentation, CSM, APTA. *JOSPT* 23(1):64, 1996
49. Grigg P: Peripheral neural mechanisms in proprioception. *J Sports Rehab* 3:2-17, 1994
50. Grood ES, Noyes FR, Butler DL: Ligamentous and capsular restraints preventing straight medial and lateral laxity in intact human cadaver knees. *J Bone Joint Surg* 63:1257-1269, 1981
51. Gross MT: Effect of recurrent lateral ankle sprains on active and passive judgements of joint position. *Phys Ther* 67(10):1505-1509, 1987
52. Hageman PA, Leibowitz JM, Blanke D: Age and gender effects on postural control measures. *Arch Phys Med Rehab* 76:961-965, 1995

53. Hall M, Ferrell W, Sturrock R, Hamblen D, Baxendale R: The effect of the hypermobile syndrome on knee joint proprioception. *Br J Rheum* 34:121-125, 1995
54. Harner CD, Paulos LE, Greenwald AE, Rosenberg TD, Cooley VC: Detailed analysis of patients with bilateral anterior cruciate ligament injuries. *Am J Sports Med* 22(1):37-43, 1994
55. Harrison E, Duenkel N, Dunlop R, Russell G: Evaluation of single leg standing following ACL surgery and rehabilitation. *Phys Ther* 74(3):245-253, 1994
56. Harter RA, Osternig LR, Singer KM, James SL, Larson RL, Jones DC: Long-term evaluation of knee stability and function following surgical reconstruction for anterior cruciate ligament insufficiency. *Am J Sports Med* 16(5):434-443, 1988
57. Hawkins RJ, Misamore GW, Merritt TR: Follow-up of the acute non-operated isolated ACL tear. *Am J Sports Med* 14(3):205-210, 1986
58. Higgins MJ, Perrin DH: Comparison of weight-bearing and non-weight-bearing conditions on knee joint reposition sense. *J Sports Rehab* 6:327-334, 1997
59. Hoppenfeld S: Physical examination of the spine and extremities. New York: Prentice Hall, Inc. 1976
60. Horak FB: Clinical Measurement of postural control in adults. *Phys Ther* 67(12):1881-1885, 1987
61. Howorth MB: General relaxation of the ligaments. *Clin Orthop Rel Res* 30:133-142, 1963
62. Hughston JC, Andrews JR, Cross MJ, Moschi A: Classification of knee ligament instabilities, part I., the medial compartment and cruciate ligaments. *J Bone Joint Surg* 58A(2):159-172, 1976
63. Hurley MV, Newham DJ: The influence of arthrogenous muscle inhibition on quadriceps rehabilitation of patients with early unilateral osteoarthritic knees. *Brit J Rheum* 32:127-131, 1993
64. Huston LJ, Wojtys EM: Neuromuscular performance characteristics in elite female athletes. *Am J Sports Med* 24(4):427-436, 1996
65. Ihara H, Nakayama A: Dynamic joint control training for knee ligament injuries. *Am J Sports Med* 14(4):309-315, 1986
66. Jacobsen K: Osteoarthrosis following insufficiency of the cruciate ligaments in man. *Acta Orthop Scand* 48:520-526, 1977



67. Kalenak A, Morehouse CA: Knee stability and knee ligament injuries. *JAMA* 234(11):11443-1145, 1975
68. Kaltenborn FM, Evjenth O: Manual mobilization of the extremity joints: basic examination and treatment techniques, (4<sup>th</sup> ED), Oslo, Norway: Olaf Norlis Bokhandel Universitets-gaten, 1989
69. Kapandji IA: The physiology of the joints, volume two lower limb (2<sup>nd</sup> ED), New York: Churchill Livingstone, Inc. 1970
70. Kendall HO, Kendall FP, Wadsworth GE: Muscles Testing and Function (2<sup>nd</sup> ED), Baltimore: Williams and Wilkins, Inc. 1971
71. Kennedy JC, Alexander IJ, Hayes KC: Nerve supply of the human knee and its functional importance. *Am J Sports Med* 10(6):329-335, 1982
72. Kirk J, Ansell B, Bywaters E: The hypermobility syndrome. Musculoskeletal complaints associated with generalized joint hypermobility. *Ann Rheum Dis* 26:419-425, 1967
73. Klemp P, Learmonth ID: Hypermobility and injures in a professional ballet company. *Brit J Sports Med* 18(3):143-148, 1984
74. Krauspe R, Schmidt M, Schaible HG: Sensory innervation of the ACL, an electrophysiological study of the response properties of single identified mechanoreceptors in the cat. *J Bone Joint Surg* 74(3):390-397, 1992
75. Lepart SM, Pincivero DM, Giraldo JL, Fu FH: The role of proprioception in the management and rehabilitation of athletic injuries. *Am J Sports Med* 25(1):130-137, 1997
76. Lephart SM, Perrin DH, Fu FH, Cieck JH, McCue FC, Irrgang JJ: Relationship between selected physical characteristics and functional capacity in the anterior cruciate ligament-insufficient athlete. *JOSPT* 16(4):174-181, 1992
77. Lewis JL, Shybut GT: In vivo forces in the collateral ligaments of canine knees. *Trans Orthop Res Soc* 6(4), 1981
78. Lewkonja RM: Does generalised articular hypermobility predispose to generalised osteoarthritis? *Clin Experimental Rheum* 4:115-119, 1986
79. Lofvenberg R, Karrholm J, Sundelin G, Ahlgren O: Prolonged reaction time in patients with chronic lateral instability of the ankle. *Am J Sports Med* 23(4):414-417, 1995

80. Lord SR, Caplan GA, Ward JA: Balance, reaction time, and muscle strength in exercising and nonexercising older women: a pilot study. *Arch Phys Med Rehab* 74:831-839, 1993
81. Loudon J, Jenkins W, Loudon K: The relationship between static posture and ACL injury in female athletes. *JOSPT* 24(2):91-97, 1996
82. Lu CL, Yu B, Basford JR, Johnson MF, An KN: Influences of cane length on the stability of stroke patients. *J Rehab Res Develop* 34(1):91-100, 1997
83. Lysholm J, Gillquist J: Evaluation of knee ligament surgery results with special emphasis on use of a scoring scale. *Am J Sports Med* 10(3):150-153, 1982
84. Magee DJ: *Orthopedic physical assessment* (3<sup>rd</sup> ED), Philadelphia: WB Saunders, Co., 1997
85. Marks R, Cantin D: Symptomatic osteoarthritis of the knee: the efficacy of physiotherapy. *Physiother* 83(6):306-311, 1997
86. McLeod WD, Hunter S: Biomechanical analysis of the knee. *Phys Ther* 60(12):1561-1564, 1980
87. Menard D: Neuromuscular considerations. In: *Orthopedic assessment and treatment of the geriatric patient*, St. Louis: Mosby, 1993
88. Mizuta H, Sharaishi M, Kubota K, Kai K, Takagi K: A stabilometric technique for evaluation of functional instability in anterior cruciate ligament-deficient knee. *Clin J Sports Med* 2:235-239, 1992
89. Moretz JA, Walters R, Smith L: Flexibility as a predictor of knee injuries in college football players. *Phys Sports Med* 10(7):93-97, 1982
90. Murray MP, Seireg AA, Sepic SB: Normal postural stability and steadiness: quantitative assessment. *J Bone Joint Surg* 57A(4):510-515, 1975
91. Nashner LM: Sensory, neuromuscular, and biomechanical contributions to human balance. In: Duncan PW, ed, *Balance, Proceedings of the APTA Forum*, 5-12, 1990
92. Nicholas JA: Injuries to knee ligaments, relationship to looseness and tightness in football players. *JAMA* 212(13):2236-2239, 1970
93. Noyes FR, Grood ES, Butler DL, Ratterman L: Knee ligament tests, what do they really mean? *Phys Ther* 60(12):1578-1581, 1980

94. Noyes FR, Barber SD, Mooar LA: A rationale for assessing sports activity levels and limitations in knee disorders. *Clin Ortho Rel Res* 246:238-249, 1989
95. Noyes F, Barber S, Mangine R: Abnormal lower limb symmetry determined by function hop tests after ACL rupture. *Am. J Sports Med* 19(5):513-518, 1991
96. O'Connor BL, Palmoski MJ, Brandt KD: Neurogenic acceleration of degenerative joint lesions. *J Bone Joint Surg* 67A(4):562-571, 1985
97. Patla A, Frank J, Winter D: Assessment of balance control in the elderly: major issues. *Physiother Canada* 42(2):89-97, 1990
98. Perry J: Gait analysis: normal and pathological function. Thorofare, (NJ): Slack, 1992
99. Pope MH, Johnson RJ, Brown DW, Tighe C: The role of the musculature in injuries to the medial collateral ligament. *J Bone Joint Surg* 61A(3):398-402, 1979
100. Prieto TE, Myklebust JB, Hoffman RG, Levetl EG, Myklebust BM: Measures of postural steadiness: differences between healthy young and elderly adults. *IEEE Trans Biomed Eng* 43(9):956-966, 1996
101. Qualter R, Kowalsky D, Helgren M: The reliability and validity of a unilateral balance and contralateral reach test for ACL insufficiency. Platform Presentation, CSM, APTA. *JOSPT* 23(1):91, 1996
102. Radin EL, Yang KH, Riegger C, Kish VL, O'Connor JJ: Relationship between lower limb dynamics and knee joint pain. *J Orthop Res* 9(3):398-405, 1991
103. Rowinski MJ: Afferent neurobiology of the joint. In: Gould JA (ed), *Orthopaedic and sports physical therapy*, (2<sup>nd</sup> ED), pp 49-63, St. Louis: CV Mosby Co., 1990
104. Schenkman M: Interrelationship of neurological and mechanical factors in balance control. In: Duncan PW, ed. *Balance*, Proceedings of the APTA Forum, 29-41, 1990
105. Scott D, Bird H, Wright V: Joint laxity leading to osteoarthritis. *Rheum and Rehab* 18(3):167-169, 1979
106. Shoemaker SC, Markolf KL: Effects of joint load on the stiffness and laxity of ligament-deficient knees. *J Bone Jt. Surg* 67A(1):136-146, 1985
107. Shrout PE, Fleiss JL: Intraclass correlations: Uses in assessing rater reliability. *Psych Bulletin* 86(2):420-428, 1979
108. Skinner HB, Barrack RL, Cook SD: Age related decline in proprioception. *Clin Orth Rel Res* 184:208-211, 1984

109. Skinner HB, Wyatt MP, Stone ML, Hodgdon JA, Barrack RL: Exercise-related knee joint laxity. *Am J Sports Med* 14(1):30-35, 1986
110. Slemenda C, Brandt KD, Heilman DK, Mazzuca S, Braunstein EM, Katz BP, Wolinsky FD: Quadriceps weakness and osteoarthritis of the knee. *Ann Int Med* 127(2):97-104, 1997
111. Snyder-Mackler L, Fitzgerald G, Barolozzi A, Ciccotti M: Relationship between passive joint laxity and functional outcome after ACL injury. *Am. J Sports Med* 25(2):191-195, 1997
112. Solomonow M, Baratta R, Zhou BH, Shoji H, Bose W, Beck C, D'Ambrosia R: The synergistic action of the ACL and thigh muscles in maintaining joint stability. *Am J Sports Med* 15(3):207-213, 1987
113. Steiner ME, Grana WA, Chillag K, Schelberg-Karnes E: The effect of exercise on anterior-posterior knee laxity. *Am J Sports Med* 14(1):24-29, 1986
114. Sutro CJ: Hypermobility of bones due to over-lengthened capsular and ligamentous tissues; a cause for recurrent intra-articular effusion. *Surgery* 21:67, 1947
115. Tegner Y, Lysholm J, Lysholm M, Gillquist J: A performance test to monitor rehabilitation and evaluate ACL injuries. *Am J Sports Med* 14(2):156-159, 1986
116. Tibone J, Antich T, Fanton G, Moynes D, Perry J: Functional analysis of ACL instability. *Am J Sports Med* 14(4):276-282, 1986
117. Tropp H, Ekstrand J, Gillquist J: Stabilometry in functional instability of the ankle and its value in predicting injury. *Med Sci Sports Ex* 16(1):64-66, 1984
118. Tropp H, Odenkirk P: Postural control in single limb stance. *J Orth Res* 6(6):833-839, 1988
119. Trulock SC, Guskiewicz KM, Prentice WE, Shields EW: A comparison of static, dynamic, and functional methods of balance assessment. (Unpublished thesis) 1997, University of North Carolina, Chapel Hill
120. Van Parys JAP, Njikiktjen CJ: Romberg's sign expressed in a quotient. *Agressologie* 17(B) special:95-99, 1975
121. Wallace LA, Mangine RE, Malone TR: The knee. In: Gould JA (ed), *Orthopaedic and sports physical therapy* (2<sup>nd</sup> ED), pp 323-345, St. Louis: CV Mosby Co., 1990

122. Wegner L, Kisner C, Nichols D: Static and dynamic balance responses in persons with bilateral knee osteoarthritis. *JOSPT* 25(1):13-18, 1997
123. Williams and Warwick, (eds), *Grays Anatomy* (36<sup>th</sup> ED), pp 393-490, Philadelphia: WB Saunders Co., 1980
124. Winter DA: *Biomechanics and motor control of human movement* (2<sup>nd</sup> ED), New York: John Wiley & Sons, Inc. 1990.
125. Woodford-Rogers B, Cyphert L, Denegar CR: Risk factors for ACL injury in high school and college athletes. *J Athl Train* 29(4):343-346, 1994
126. Wyke B: Articular neurology-a review. *Phys Ther* 58:94-98, 1972
127. Zatterstrom R, Frieden T, Lindstrand A, Moritz U: The effect of physiotherapy on standing balance in chronic ACL insufficiency. *Am J Sports Med* 22(4):531-536, 1994